AN ELECTRONIC FEEDBACK SYSTEM FOR AMPLITUDE STABILIZATION OF A HELIUM-NEON GAS LASER

A THESIS

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AN ELECTRONIC FEEDBACK SYSTEM FOR AMPLITUDE STABILIZATION

OF A HELIUM-NEON GAS LASER

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SUMMARY

The basic helium-neon gas laser cavity is composed of a long cylindrical glass discharge tube containing a mixture of helium and neon gases, a pair of dielectric mirrors located on and perpendicular to the axis of the discharge tube, and an iris located between one end of the discharge tube and a cavity mirror. The laser cavity is subject to unwanted mechanical, acoustic, thermal, and pressure disturbances inherent in its environment. These unwanted disturbances promote vibrations of the critically aligned cavity mirrors and iris and produce spurious amplitude fluctuations in the intensity of the laser beam.

To substantially reduce these amplitude fluctuations, an electronic feedback system has been designed, constructed, and tested. The system is composed of a radio frequency excited helium-neon gas laser, a photomultiplier light intensity detector, a dc amplifier, an amplitude modulator, and a 120 watt, 28 MHz exciting amplifier arranged in a feedback loop. The amplitude fluctuations of the laser output are detected, amplified, and applied with phase reversal to the amplitude modulator. The modulator then varies the output power of the exciting radio frequency amplifier, which in turn varies the amplitude of the laser beam, counteracting the original amplitude fluctuation of the laser.

Spurious fluctuations are reduced by a factor of more than a hundred, and the system provides amplitude stability over a wide range of intensities. Because most amplitude fluctuations occur at mechanical resonant frequencies of the laser cavity and supporting structure in the

10-150 Hz range, no effort is made to extend the 500 Hz upper cutoff frequency of the system. This electronic feedback system provides an easily implemented, relatively inexpensive solution to the low frequency amplitude stabilization problem of gas lasers.

CHAPTER I

INTRODUCTION

The Problem

A helium-neon gas laser consists of a discharge tube containing a mixture of helium and neon gases and is excited by a discharge of current passing through the gases. Laser action comes about when a pair of external mirrors located on and perpendicular to the axis of the excited discharge tube are brought into exact parallelism. Mechanical, acoustical, thermal, and pressure disturbances inherent in the environment of the laser mirrors and supporting structure produce unwanted intensity fluctuations of the laser beam. These fluctuations are of low frequency, occurring at the mechanical resonant frequencies of the laser cavity and supporting structure in the 10-150 Hz range.

Literature Review

Rigden and White (1) of Bell Telephone Labs were the first to quantitatively correlate the output of an helium-neon gas laser beam with the magnitude of the exciting current for the 6,328 Å emission. Since their paper in 1962, emphasis has shifted toward frequency stabilization with amplitude stabilization playing a minor role. In 1963, Jaseja, Javana, and Townes (2) of the Massachusetts Institute of Technology in their study of frequency stability of the helium-neon laser, described the precautions they took to prevent mirror motion of their free running laser. Their laser was supported on a massive shock-mounted table with resonant frequencies of many seconds in a cellar of an isolated building where noise and ground tremors were very small. They also found that it was necessary to avoid various acoustic vibrations such as those from running equipment and high winds. Their calculations indicated that a mirror movement of only $5x10^{-13}$ centimeters would cause a frequency shift of 1.5 KHz. Constant separation of the mirrors was insured by spacers of uniform cross-section with very low thermal expansion coefficient placed between the cavity mirrors. They also noted a 120 Hz pulsation of the laser amplitude output due to residual ripple in the power supply's output voltage.

Other types of unwanted amplitude fluctuations treated in the literature are described in papers by Prescott and Van der Zeil (3), Bailey and Sanders (4), and Bellisio, Freed, and Haus (5). These papers discuss amplitude variations due to thermal agitation of the laser gases within the discharge tube and the irregular discharge of the exciting current in the helium-neon gas. The fluctuations produced by these phenomena are many orders of magnitude below the disturbances due to mechanical vibration and are not treated further in this thesis.

The most sophisticated work to date in frequency and limited amplitude control was reported by Shimoda and Javan (6) of the Massachusetts Institute of Technology in late 1964. Their stabilization system utilized three servo feedback controls: one to adjust the tilt of the cavity mirrors, a second to change the separation of the mirrors and a third to very the exciting radio frequency discharge. However, to achieve the desired frequency stability, their laser was operated in a single mode configuration at the minimum power output level. Their excitation or amplitude control system merely kept the system in a threshold condition, between no output and single mode output, and limited power to one microwatt, which was three orders of magnitude lower than maximum laser output.

In answer to the needs for a constant amplitude laser of higher power, Met (7) presented an open loop amplitude stability system for the helium-neon laser in 1965. This system operated in a three mode configuration providing about ten times the power of the single mode configuration. Met was able to slowly rotate in a cyclic manner one of the laser cavity mirrors; in doing so, he was able to keep at least one of the three modes above the threshold condition. He showed that this changing of modes had an averaging effect and tended to decrease the amplitude fluctuations of the total output of the laser. Met reported an amplitude fluctuation reduction of 10 to 100, but the photographs accompanying his paper showed reductions much less than ten. Although the three mode configuration had higher output power than the single mode, for long, 150 centimeter lasers, only about 10 per cent of the laser's maximum power was utilized.

The need for high power amplitude stabilized helium-neon lasers exists in many applications. Long range amplitude modulated communication systems and velocity measurements of viscous liquids require not only a constant amplitude laser beam, but in addition, require a high power output to enable a detector to receive the desired information.

Background Information

The advent of the laser has opened new vistas in the fields of communication and measurements. In communication, the 10^{14} Hz frequency of the laser light is orders of magnitude higher than any previously used radio frequency carrier, allowing a large bandwidth and extreme directivity. In measurements, the reflectivity properties of light and its extremely small wavelength make possible accuracies never before obtainable.

Ideally, the laser output should be constant in amplitude and singular in frequency. Unfortunately, the helium-neon gas laser possesses neither of these attributes. Mechanical, acoustical, thermal, and pressure disturbances inherent in the environment of the laser produce amplitude fluctuations of up to 100 per cent in the intensity of the laser beam. Instead of a single frequency spectrum, the helium-neon laser has a bell-shaped band of discrete frequencies uniformly spaced by an amount

$$\Delta f = \frac{c}{2d}$$

where c is the speed of light in free space and d is the distance between the cavity mirrors. The total width of the pass band, while negligibly small in terms of the laser light center frequency, is still approximately 1,000 MHz at full laser output. With this bandwidth about ten different frequencies exist simultaneously in the output of a 150 centimeter helium-neon gas laser. Historically, emphasis has been placed on the difficult problem of frequency stabilization. Work on amplitude stabilization has centered on making the laser cavity mirrors mechanically rigid and isolating the appurtenant structures from all sources of disturbances.

There are many applications of the laser in use today, ranging from welding to radar. Some applications of the laser such as welding use only the focusing property of coherent light to enable energy to be concentrated on a much smaller area than is possible with incoherent light. Some applications of the laser such as radar depend on both the laser's singular frequency and its constant amplitude for proper operation. Other applications of the laser such as distance measuring, depend only on the singular frequency of the laser and are not sensitive to variations in the amplitude of the beam. Still other applications of the laser such as the measurement of the velocity of fluids and simple amplitude modulated communication systems depend on the constant amplitude of the coherent light and are insensitive to variations in the frequency of the laser beam. Thus in this last application of the laser stabilization of the amplitude becomes the major requirement.

Purpose

The purpose of this research is to design, construct, and demonstrate the effectiveness of an electronic feedback system in stabilizing the amplitude of an helium-neon gas laser. The operating characteristics of the laser and exciting amplifier were investigated to find a means of varying the input current of the laser in a manner that compensates for the unwanted amplitude fluctuations due to mechanical vibrations of the components of the laser cavity. Entailed in the design of this system is the design and construction of each of the system components: a light intensity detector, a dc amplifier, an amplitude modulator, and a 120 watt radio frequency amplifier.

Data will be presented to demonstrate the effectiveness and limitations of the feedback system. Specific parameters of importance to be determined are the maximum amplitude and maximum frequency of fluctuation rate that the system design is capable of substantially reducing.

The feedback system's components are described in Chapter II. The procedures followed in the design and implementation of the system are discussed in Chapter III. In Chapter IV the system's performance is analyzed and the results are given in Chapter V. The conclusions drawn from the results of the system tests are given in Chapter VI.

CHAPTER II

SYSTEM DESIGN AND CONSTRUCTION

The Laser

The laser beam to be amplitude stabilized is generated by an helium-neon gas laser, operating at a wavelength of 6,328 Å and employing external mirrors placed 143 centimeters apart. A pictorial diagram of this laser cavity is shown in Figure 1. A discharge tube is mounted between the cavity mirrors and filled with a five to one mixture of neon and helium gas at a pressure of 10^{-3} milimeters of mercury. The ends of the discharge tube from which the laser beam emerges are optically flat windows sloped to the Brewster angle to minimize reflection of the laser beam in unwanted directions. The spherical mirrors are multi-layered dielectric mirrors located on the centerline of, and external to, the discharge tube. The mirrors have a maximum reflectivity property of 98 per cent at a wavelength of 6,328 Å. The selective reflectivity property of the mirrors enhances laser action at 6,328 Å and discriminates against the other possible wavelengths capable of helium-neon laser action in the infra-red region. An adjustable iris is also in the laser cavity, located on the centerline of the discharge tube, between one end of the discharge tube and a cavity mirror. Its purpose is to restrict the diameter, and thus the output power, of the laser beam. To obtain the single mode TM_{oo} configuration, it is necessary to close the iris to allow only the smallest possible beam and reduce excitation power to threshold condition. Because the TM_{oo} configuration is the most frequency

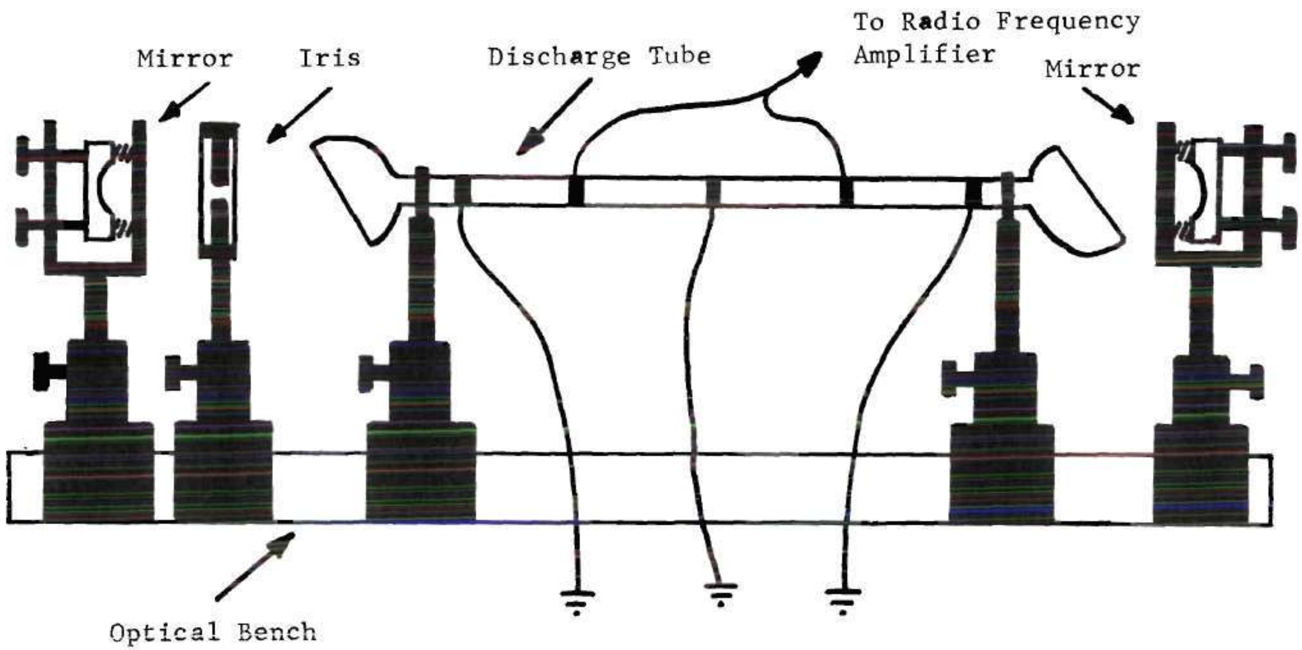


Figure 1. Pictorial Diagram of the Laser Cavity

stable mode, most frequency and amplitude stability work has been done using this mode. In designing an amplitude stabilization system three different settings of the iris are considered: a small opening producing the TM_{00} mode, a medium opening, and a maximum opening equivalent to removing the iris from the cavity and allowing a maximum power configuration.

Excitation for the laser was initially provided by a Collins 120 watt, 28 MHz continuous wave transmitter. However, it was necessary to design and construct a 120 watt radio frequency amplifier that could be control grid modulated and had a wide-band frequency response. The Collins transmitter was then used as an exciter for this amplifier. The laser cavity was crudely shock mounted on an optical bench assembly, with each component of the cavity: the discharge tube, the iris, the two mirrors, independently fixed to the bench. The optical bench assembly was mounted on a heavy wooden table covered with brass ground screen. The table was supported on six one-inch thick rubber pads and was located on the fourth floor of a brick building.

Output Characteristics of the Helium-Neon Laser

Methods of varying the intensity of the laser beam were studied to determine the simplest and most economical process to implement. Modulating the plate voltage of the 120 watt radio frequency amplifier appeared to solve the problem initially, but the size, power handling capability, and cost of such a modulation system was prohibitive. Further study included control grid modulation, which was found to satisfy the set criterion quite well. The control grid modulator required only 1.5 watts of supply power and was easily adapted to the radio frequency amplifier. Primary interest in the modulation schemes considered was the overall input-output characteristics of the amplifier-laser-detector subsystem. The detector is a RCA 7102 photomultiplier tube with the anode voltage set to 700 volts. Measurements which were taken are displayed in Figures 2, 3, and 4 as the sub-system's overall characteristics. The figures depict the relationship between the normalized output current of the photomultiplier tube as a function of the control grid bias voltage of the radio frequency amplifier. Three sets of data are shown, one for each of the three iris settings. Although the characteristic curves are nonlinear, all three curves have regions which are approximately linear. The linear region of the characteristic curves were used as the transfer function of the sub-system in the design of the other components of the feedback system. As can be seen from Figures 2, 3, and 4, the linear region of the characteristic curves included more than 75 per cent of the output intensity range of the laser, indicating that control over a useful wide range of amplitudes was possible with a linear feedback control system.

System Formulation

A system utilizing the characteristics of the laser output was designed to reduce unwanted fluctuation of the laser's output amplitude due to environmental disturbances, power supply ripple, and all other low frequency disturbances affecting the laser.

The feedback system shown in block diagram in Figure 5 was designed and constructed. The RCA 7102 photomultiplier tube received the incoming laser beam and converted the light energy to current. The dc amplifier following the photomultiplier tube amplified the output current

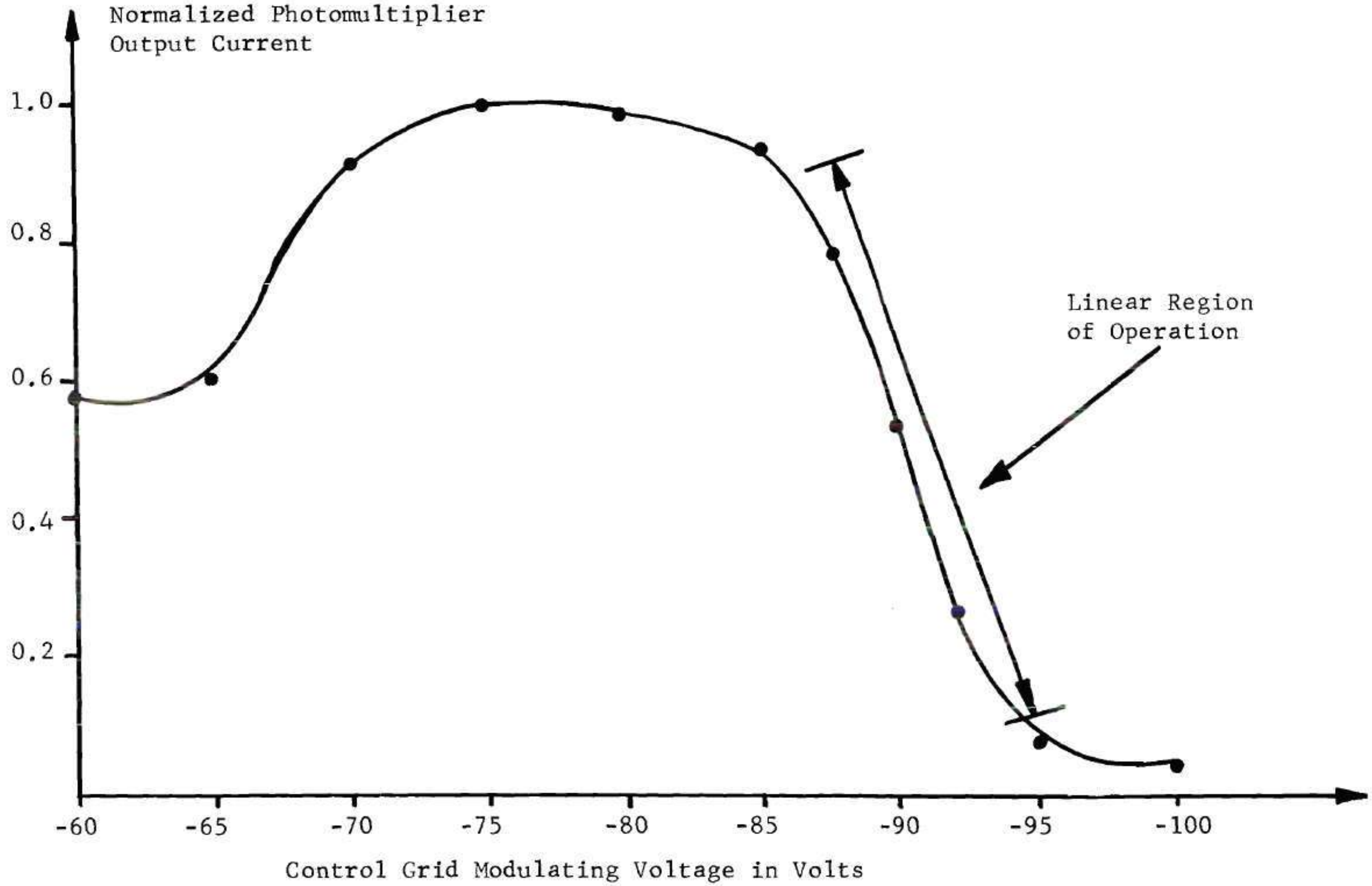


Figure 2. Exciter-Laser-Detector Transfer
Characteristics, Small Iris Opening

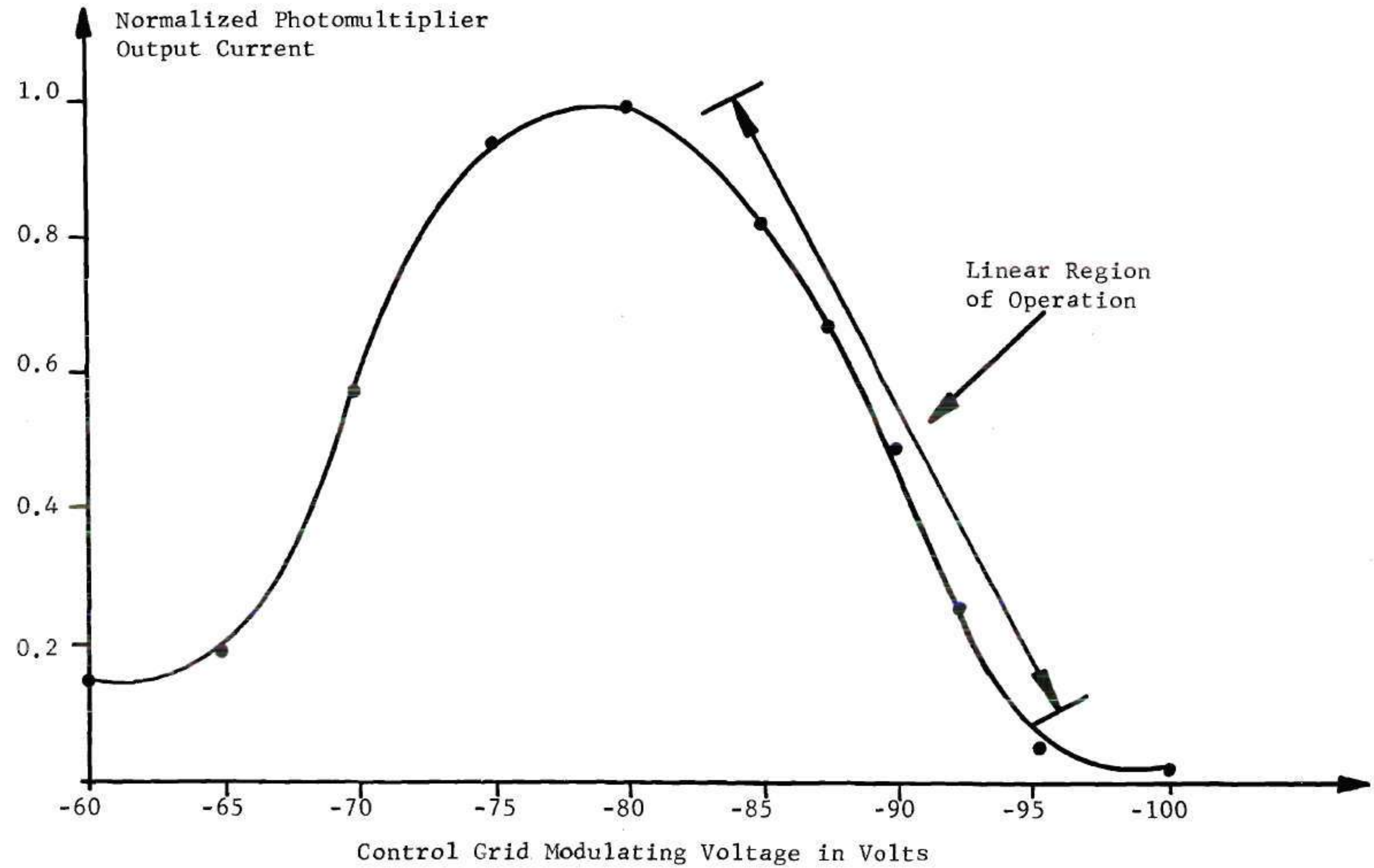


Figure 3. Exciter-Laser-Detector Transfer Characteristics, Medium Iris Opening

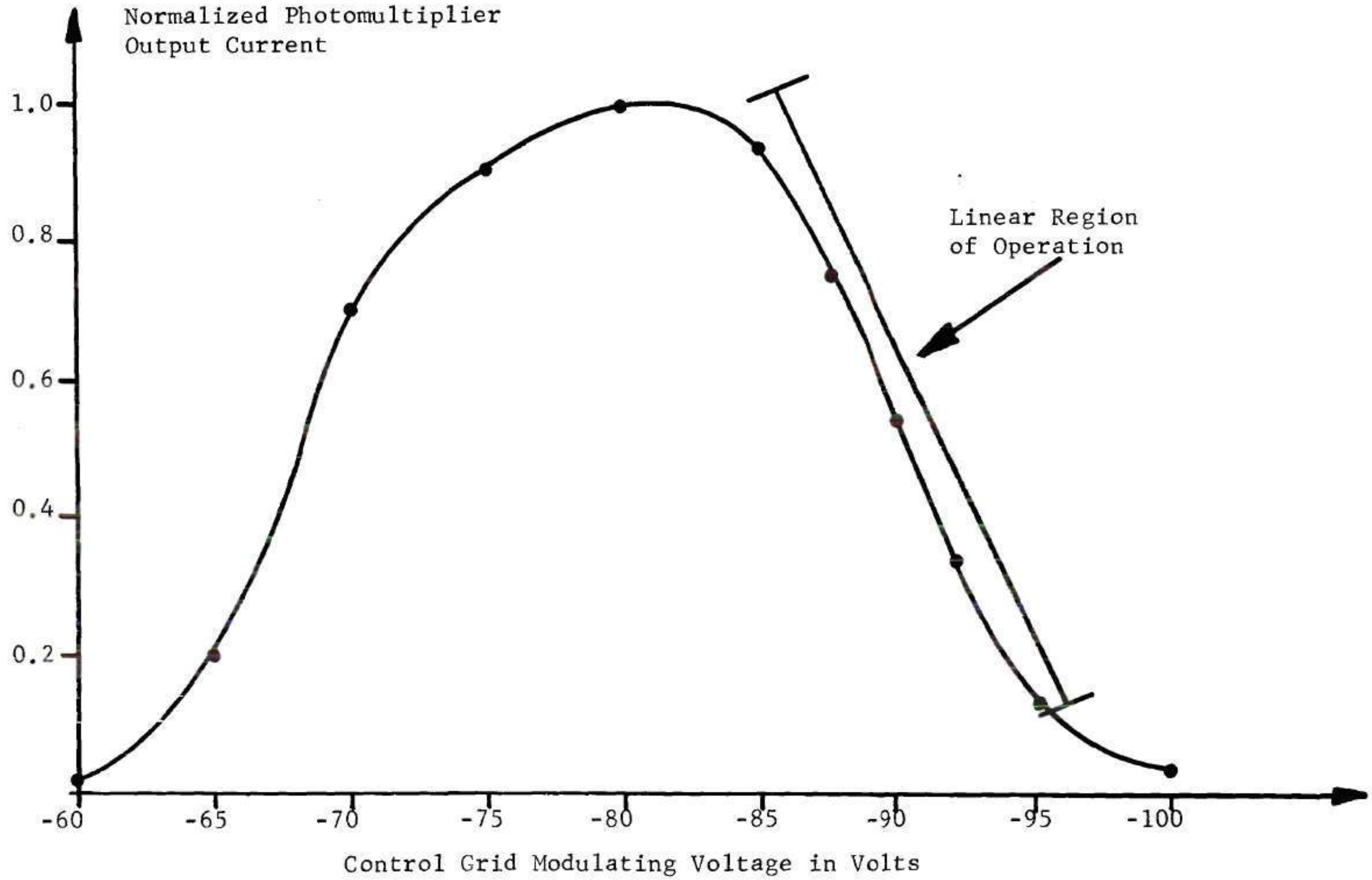


Figure 4. Exciter-Laser-Detector Transfer Characteristics, Large Iris Opening

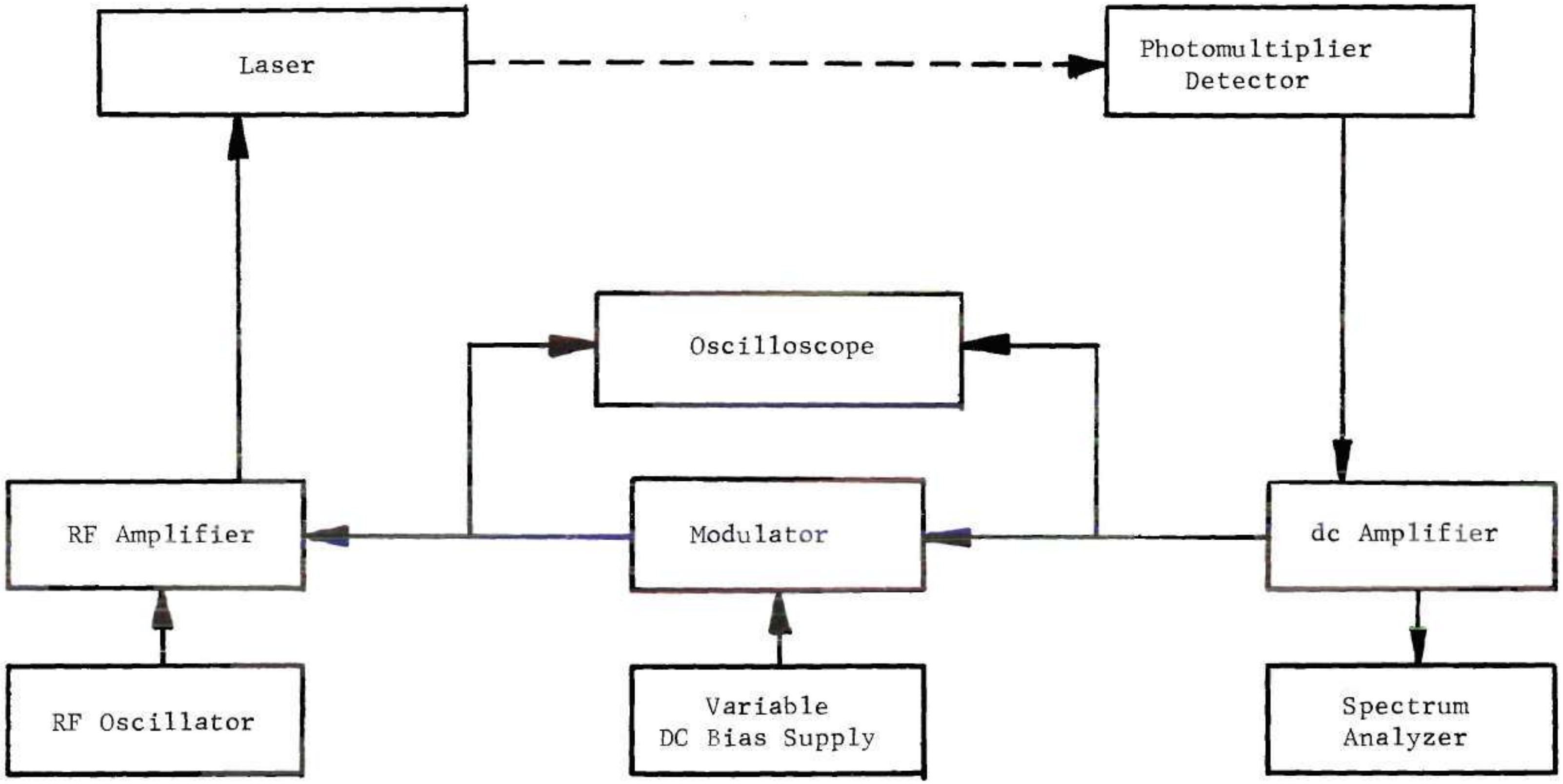


Figure 5. Block Diagram of Feedback Control System

and supplied the modulator with the fluctuation signal. The dc amplifier was capacitively coupled to the modulator to permit any desired dc level of operation while passing the fluctuation signal. The modulator had two functions; to serve as a controllable gain amplifier and as a phase inverter to change the fluctuation signal to a corrective control signal. The modulator's output load was the grid bias resistor of the 120 watt radio frequency exciting amplifier. A large grid bias supply was added in series with the modulator's variable bias to adjust the operating point to the linear portion of the amplifier-laser-detector output characteristic curve. The 120 watt radio frequency amplifier was designed for wide band operation, thus having no tuned circuits. The Collins transmitter, acting as an oscillator-exciter, determined the frequency and maximum amplitude of laser excitation. Harmonic suppressors were included in the radio frequency amplifier design to eliminate power wasted in spurious signals.

The physical arrangement of the equipment was an important factor in electromagnetic shielding of the photomultiplier detector, the dc amplifier, and the amplitude modulator. The system was located on two tables, each fifteen feet long, and each covered with bronze ground screen. The half wavelength of the 28 MHz current used to excite the laser was approximately the same length as the table; each table, therefore, acted as a shorted half wave dipole. To reduce electromagnetic coupling of the tables, the tables were placed at right angles to each other and separated by as much distance as the room would allow. One table held the laser, the oscillator-exciter, the radio frequency amplifier, and its power supply. The other table held the photomultiplier detector, the dc amplifier, the modulator, and their associated power supplies.

System Components

The Oscillator-Driver

A Collins 32-A transmitter was used as the oscillator-driver for the 120 watt radio frequency amplifier. The amplifier required less than one watt of excitation to develop full output, but to increase amplitude stability of the input excitation, a 50 ohm, 10 watt resistive load for the oscillator was built into the amplifier. The output of the Collins transmitter was amplitude stabilized by an automatic loading control network within the unit. However, a small 120 Hz power supply ripple was detected.

The Radio Frequency Amplifier

Two General Electric 1625 beam power tubes in parallel operating in Class C were used to amplify the 28 MHz oscillation from the Collins transmitter to power and voltage levels sufficient for laser action using the helium-neon gas mixture as a resistive load. To accommodate spectrum widening of the 28 MHz carrier due to modulation, the amplifier was wide band, having no tuned circuits. Harmonic suppressors in the plate, screen grid, and control grid circuits insured that no power was wasted in spurious signals. Two Lambda Model 50 power supplies in series supplied the amplifier with a well filtered 700 volt plate supply voltage. The 275 volt screen grid voltage was obtained from the plate supply through a dropping resistor and an RC filter. The Lambda supplies also provided filament voltage to the amplifier.

To obtain effective control grid modulation, a large negative dc supply of -80 volts and a 60 volt peak radio frequency driving voltage were used. Matching the output of the two 1625 tubes in parallel to the discharge tube of the laser was accomplished with a 15 turn autotransformer fed three turns from the ground end. Uniform illumination of the discharge tube was accomplished by feeding the tube in two places and grounding it on each end and in the center. The schematic diagram of the amplifier is shown in Appendix A.

The Photomultiplier Detector

A photomultiplier tube combines a photosensitive cathode with a multi-electrode secondary-emission current amplifier to produce a very high output current to input light intensity ratio. The current amplification factor of the photomultiplier tube is controlled over a wide range by varying the dc voltage to the divider network supplying the successive current multiplying electrodes. A ten stage, head-on type RCA 7102 photomultiplier tube with a S-1 spectral response was used as the light detector. The 7102 photomultiplier tube was designed for maximum response in the 7000-8000 Å wavelength region. However, at the laser output of 6,328 Å, the photomultiplier was still 56 per cent effective and provided ample output current with an anode voltage supply of 680-750 volts dc, depending on the laser beam intensity. Measured output current as a function of the anode voltage for a fixed input light source is shown in Figure 6. The output current response of this tube is independent of the load resistance up to several megohms and independent of the frequency of the amplitude modulation of the input light up to 100 MHz. Operating with a 200 kilohm divider network, the output response was a linear function of light intensity over the permissible range of output current, 0-10 microamperes.

The DC Amplifier

A high gain dc transistor amplifier was designed and constructed

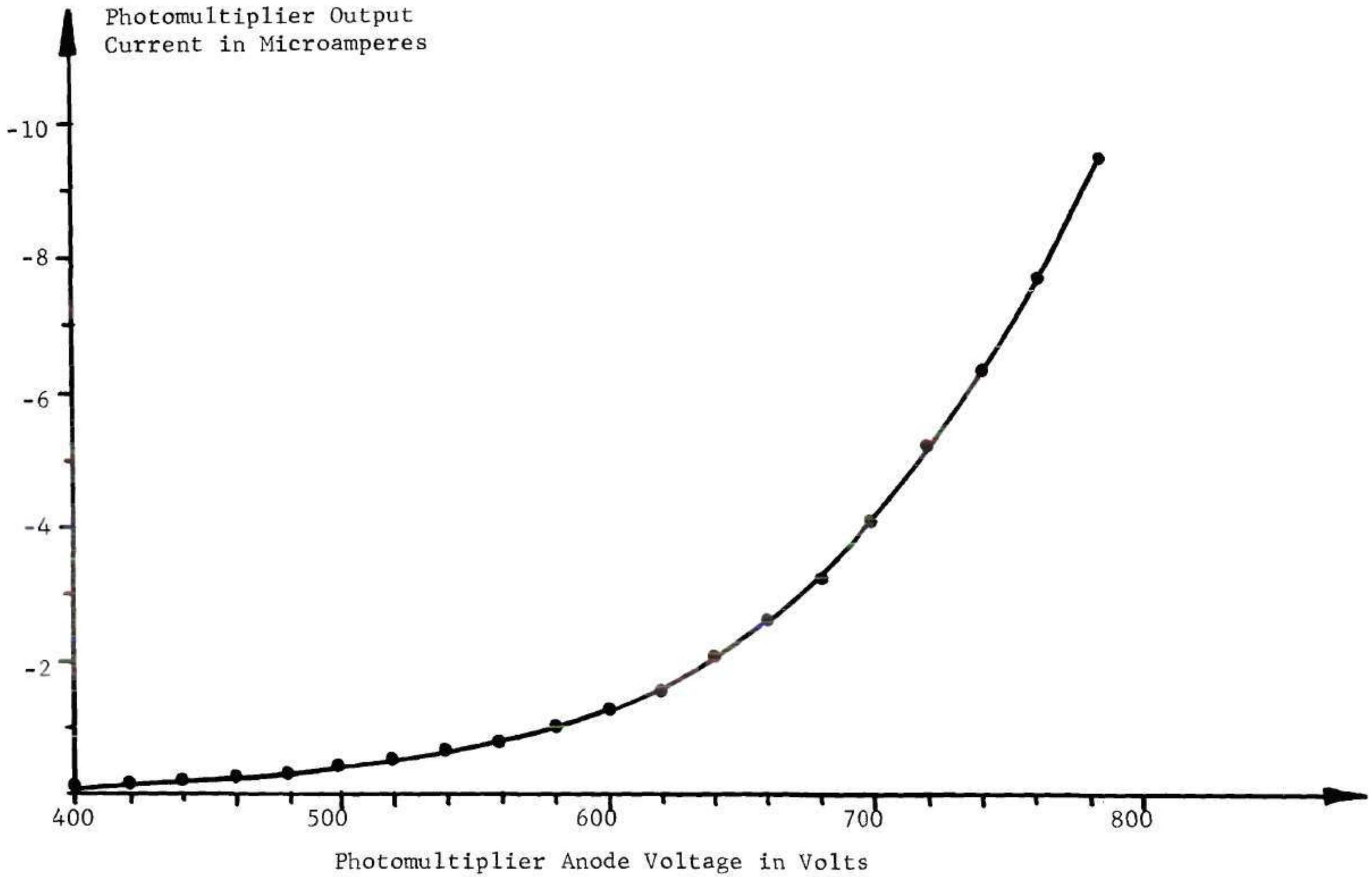


Figure 6. Photomultiplier Output Current as a Function of Anode Voltage, With a Constant Input Light Source

to couple the high impedance output of the photomultiplier to the relatively low impedance of the transistor modulator input. A 2N404 and a 2N1380 PNP alloy-junction germainium transistor in a Darlington pair configuration were used to produce a current gain of 6,800, an input impedance of 46 kilohms, and an output impedance of 330 ohms. In this configuration the output of the dc amplifier varied almost linearly from -9 to -1 volts as the input current varied from -4 to -9 microamperes, as shown in Figure 7. The collector power supply for the dc amplifier was a well filtered Hewlett Packard Model 721 A power supply delivering -10 volts. An input L section low pass filter rejected the 28 MHz exciting frequency while passing the low frequency fluctuation signals. Figures 8 and 9 show the measured frequency characteristics of the amplifier-laser-detector-dc amplifier subsystem in magnitude and phase, respectively. The schematic diagram of the photomultiplier voltage divider network and the dc amplifier is shown in Appendix B.

The Modulator

A 2N2561 PNP alloy-junction germainium medium power transistor and a 2N367 PNP transistor were used in a Darlington pair stage for the amplifier-modulator of the feedback system. A negative feedback resistor in the emitter circuit of the 2N2561 transistor increased linearity and provided a higher input impedance and thus a lower cutoff frequency due to the capacitive coupling with the dc amplifier. The calculated low frequency 3 db point was less than 0.1 Hz and the measured high frequency 3 db point was 20 KHz. The voltage transfer characteristics of the modulator with maximum gain for a 50 Hz input signal was almost linear as shown in Figure 10. From Figure 10 the maximum gain of the

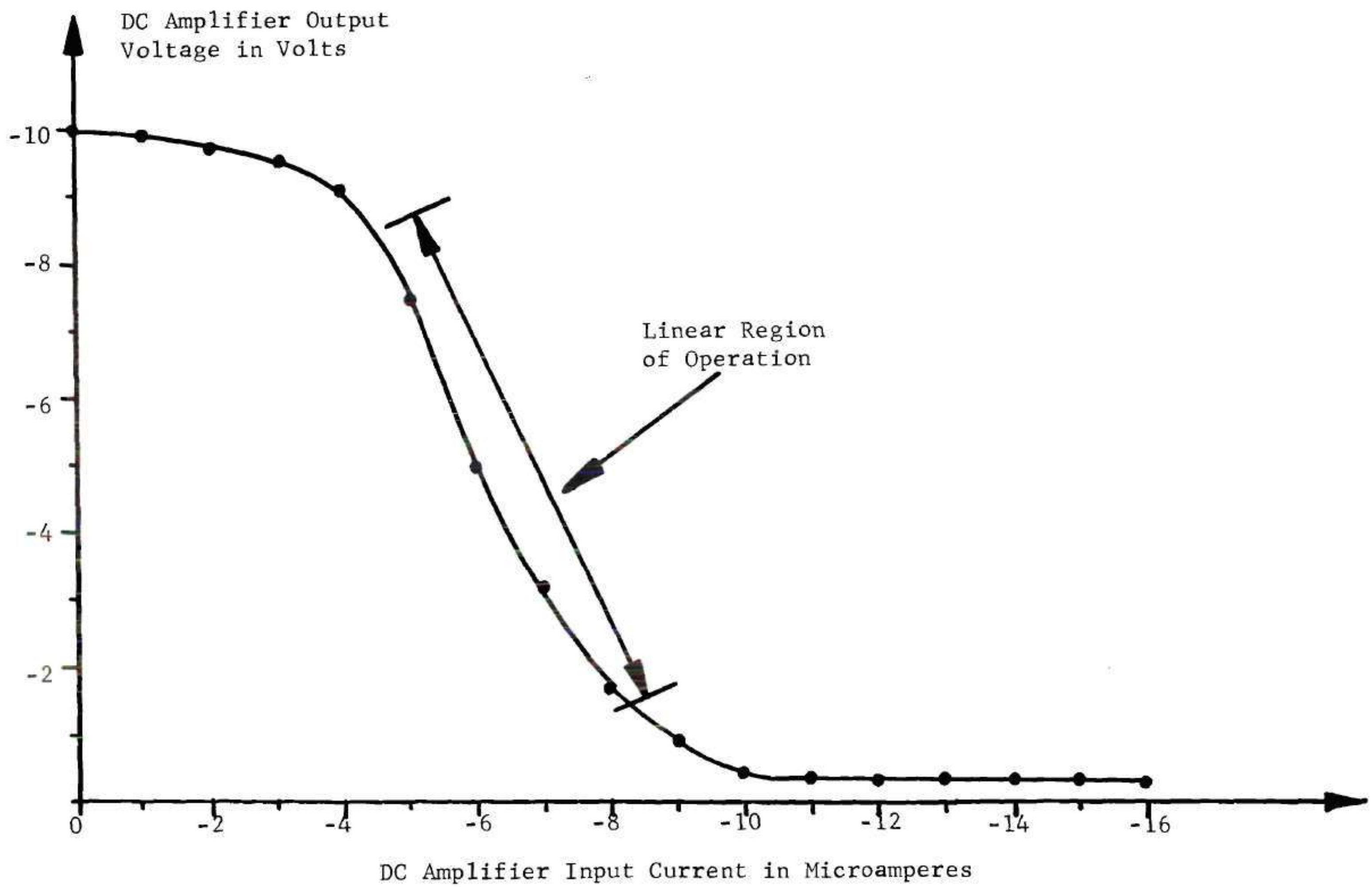


Figure 7. DC Amplifier Transfer Characteristics

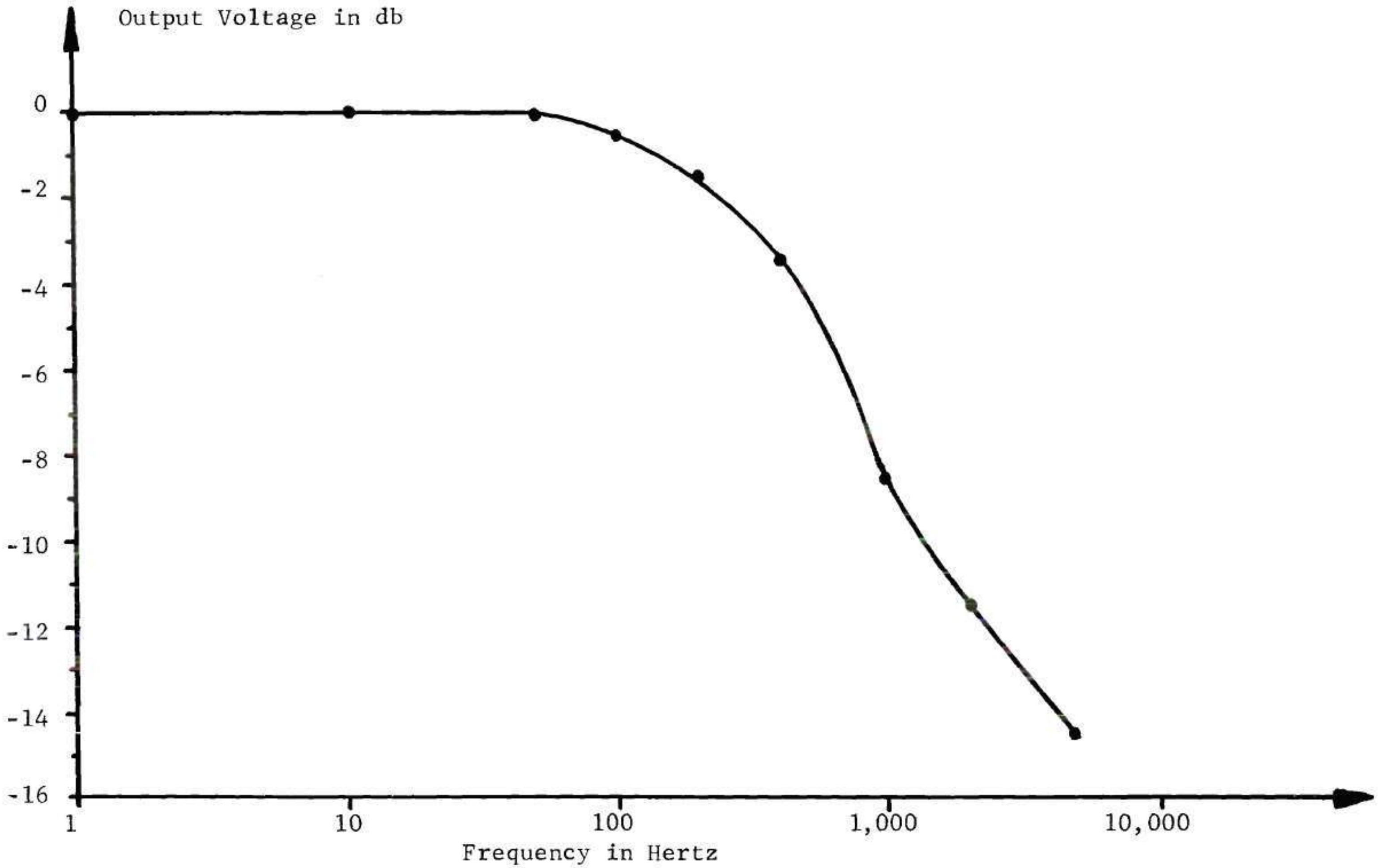


Figure 8. Amplitude Characteristics of the Exciter-Laser-Detector-DC Amplifier Subsystem as a Function of Frequency

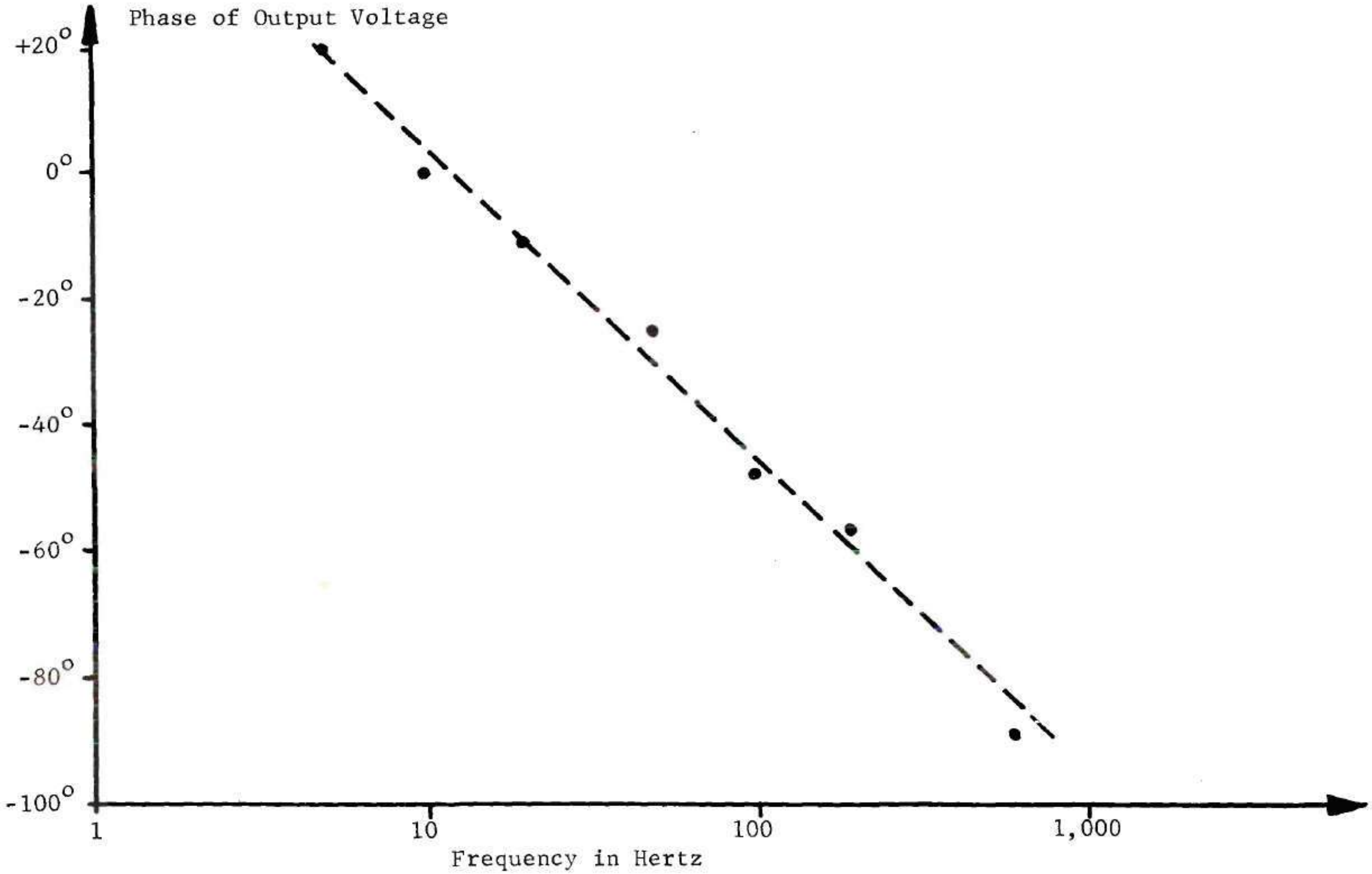


Figure 9. Phase Characteristics of the Exciter-Laser-Detector-DC Amplifier Subsystem as a Function of Frequency

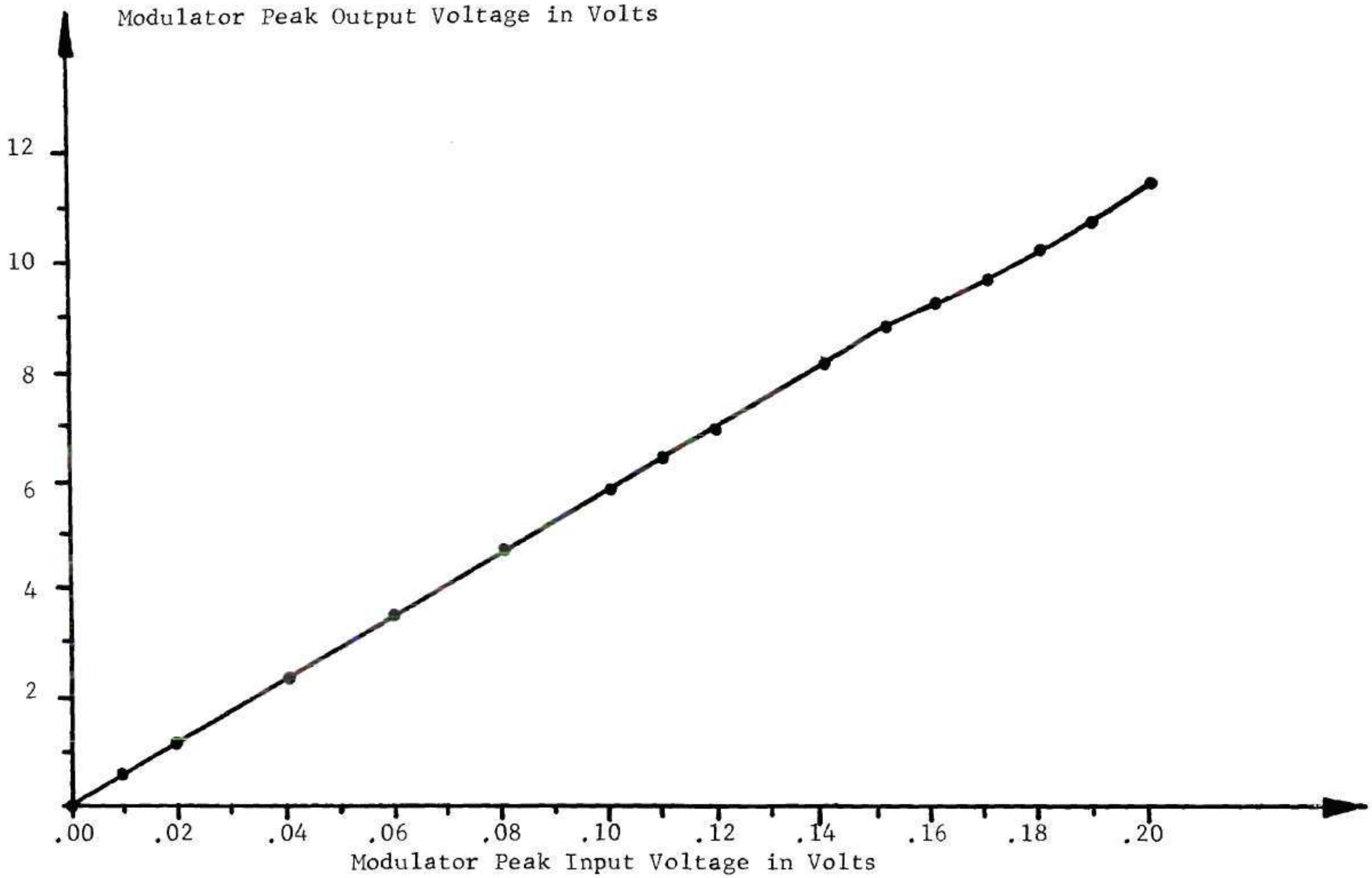


Figure 10. Modulator Transfer Characteristics
With 50 Hz Input Signal

amplifier-modulator was determined to be 57. The magnitude and phase characteristics as a function of frequency were measured and are plotted in Figures 11 and 12, respectively. The modulator also reversed the phase of the fluctuation signal which, when applied to the radio frequency amplifier, tended to significantly reduce the unwanted fluctuations present in the output of the laser. The schematic diagram of the modulator is shown in Appendix C.

The Monitors

The feedback system was continuously monitored at two points of the feedback loop with a dual trace Tektronix Model 545 B oscilloscope with a Type 1A1 plug-in unit. One monitoring point was the output of the dc amplifier which, when the system was in the open loop configuration, displayed both the dc level and the fluctuations of the laser beam intensity. The second monitoring point was the output of the amplifier-modulator. At this point with the system in the closed loop configuration, the error signal being applied to the radio frequency amplifier was monitored. As the frequency content of the laser beam intensity fluctuations were of interest, the output of the dc amplifier was also monitored by a Singer Panalyzor Model SB-12b. The Panalyzor displays the frequency spectrum of its input signal and has a resolution of five Hertz in the 0-500 Hz range.

The RF Filters and Shielding

Shielding the photomultiplier detector, dc amplifier, modulator, power supplies, and measuring equipment was a major factor in the construction of the feedback system. The radio frequency amplifier delivered approximately 60 watts of 28 MHz energy to the discharge tube

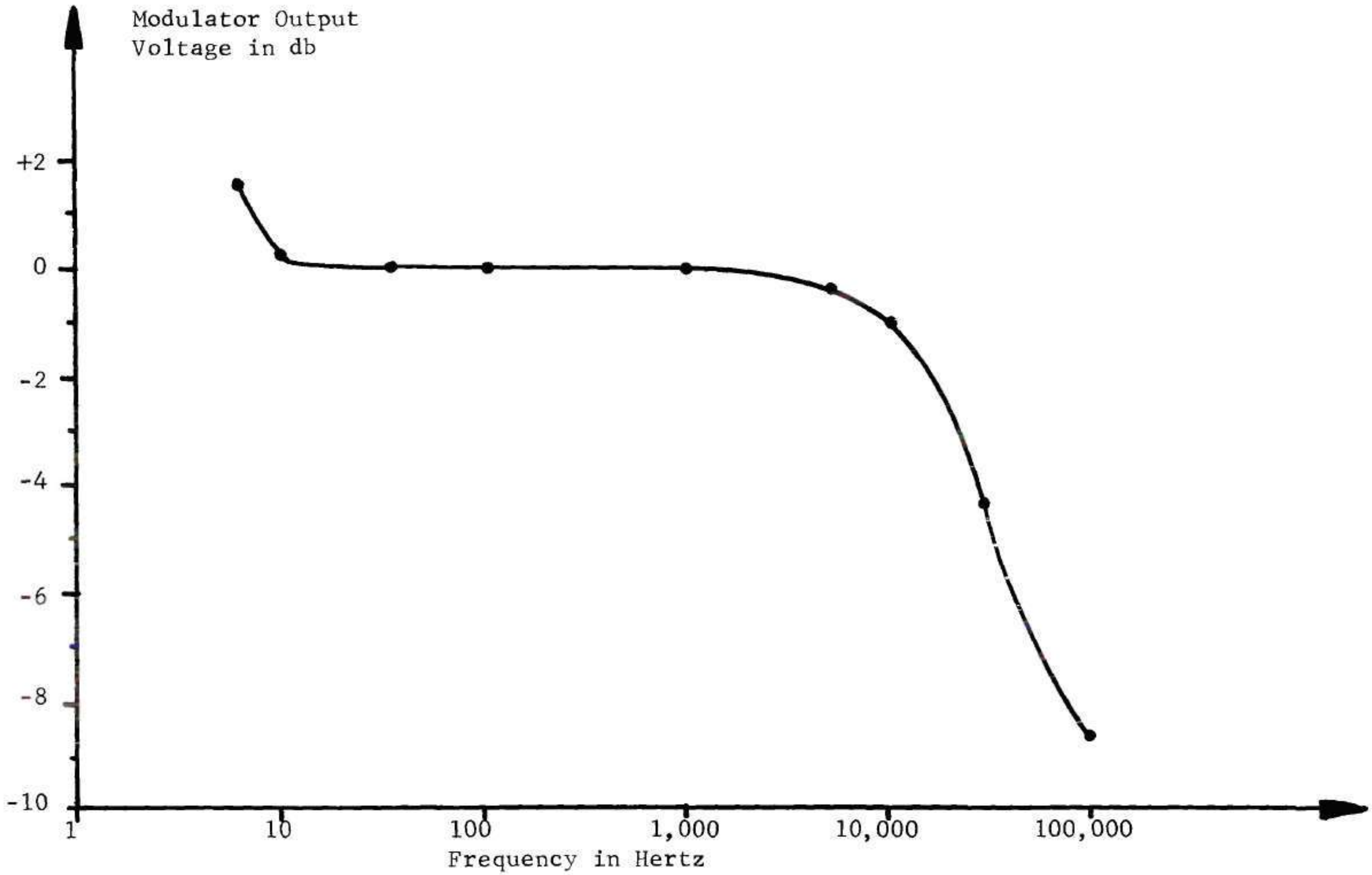


Figure 11. Modulator Amplitude Characteristics
as a Function of Frequency

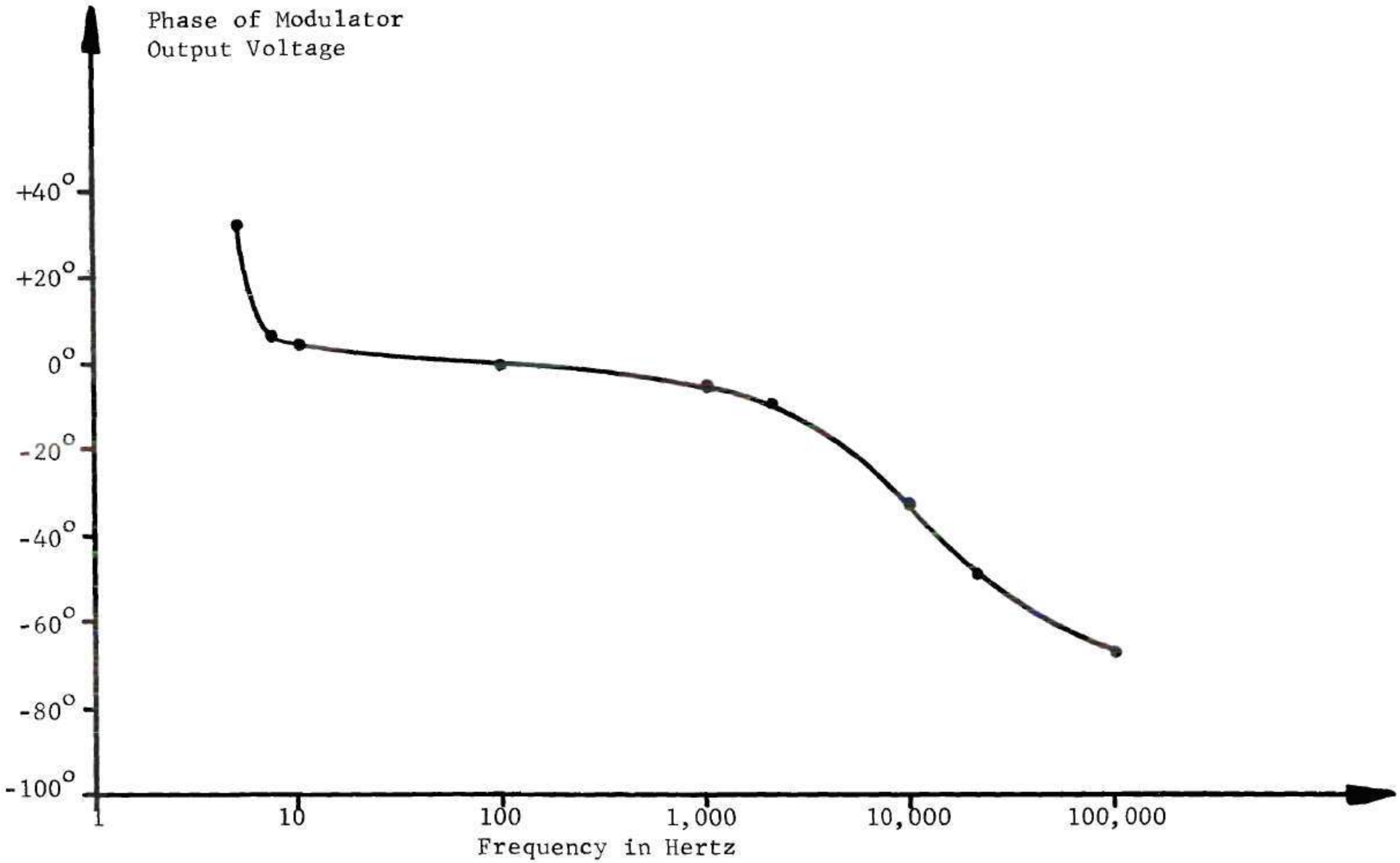


Figure 12. Modulator Phase Characteristics as a Function of Frequency

located only 20 feet from the other components of the system. To reduce radio frequency pick-up, the 7102 photomultiplier tube was housed in an aluminum box. The dc amplifier was housed in the photomultiplier box and was connected to the modulator by coaxial cable and connectors. Both the high voltage anode power supply coaxial cable and the low voltage dc amplifier power supply coaxial cables were capacitor shunted at each end. The modulator was housed in a separate aluminum box and all connections to it were coaxial. The leads to the monitors were also coaxially connected to their respective monitoring points. The modulator was connected to the radio frequency amplifier by a 20-foot coaxial cable and a radio frequency filter tuned to 28 MHz was placed at each end of this cable. One filter was in the modulator housing and the other was in the radio frequency amplifier housing. All shielding boxes, power supplies, and measuring equipment were grounded to the bronze ground screen on their respective tables. Figure 13 is a photograph of the amplifier-modulator showing coaxial signal and power supply connections, and bronze ground screen covering the supporting table.

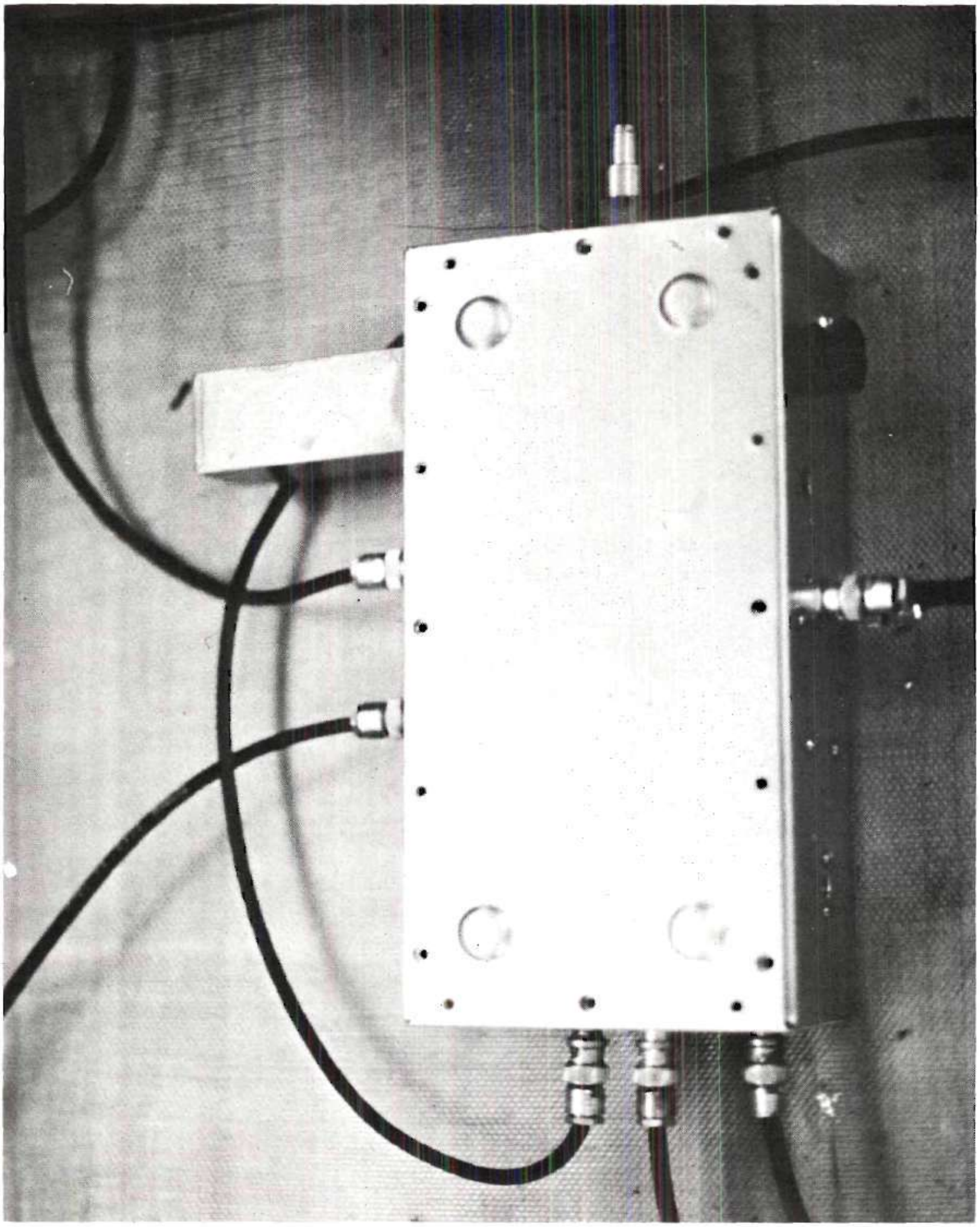


Figure 13. Amplifier-Modulator Top View, Showing Coaxial Signal and Power Supply Connections, and Bronze Ground Screen Covering Table

CHAPTER III

PROCEDURE

The major problem in this experimental thesis was finding acceptable analytic models for the various basic components of the laser transmitter and receiver systems. Measurements of subsystem characteristics were taken, recorded, and plotted to determine if linear or near linear relationships existed. The various parameters, component values, and operating points were varied and measurements taken in quest of relationships that could be dealt with analytically. In addition to the design criteria previously described, availability of material and components was also a design criterion.

The first step in the solution of the problem was the design and construction of a 120 watt radio frequency amplifier because the existing Collins 32-A transmitter was not amenable to amplitude modulation. The Collins transmitter was then used to excite the 120 watt amplifier and a 50 ohm resistive load was provided in the input circuit of the amplifier to increase excitation amplitude stability under varying grid bias conditions and to reduce reflected power to the Collins transmitter. Coupling the radio frequency amplifier to the discharge tube was a major problem in itself. As the radio frequency current is capacitively coupled to the glass discharge tube containing the helium-neon gas, the impedance of the laser was determined by experimental procedures and found to be a function of the excitation. Many tuned and untuned impedance matching networks were designed and constructed and many feed points on the discharge tube were tried in an attempt to couple as much power as possible into the helium-neon gas maxture. A simple untuned autotransformer coil which fed the discharge in two places was finally selected. The basic transmitter was then complete and work began on the receiver.

A dc amplifier was designed, built, and placed in an aluminum shielding box along with a 7102 photomultiplier tube. Care was taken to insure that maximum output of the dc amplifier did not require exceeding the maximum current rating of the photomultiplier tube. The input-output characteristics of the dc amplifier were measured and small changes in circuit component values were made to adjust its range of operating and to insure linearity.

With the receiver completed, measurements were taken to examine the fluctuations of the envelope of the received laser beam, both in amplitude and frequency to provide design data for various proposed control system schemes. Control grid modulation of the radio frequency amplifier was chosen as the control mechanism. The low cost of a control grid modulator and the linear region found in the measured dc amplifier output voltage versus control grid bias voltage characteristics of the radio frequency amplifier-laser-photomultiplier-dc amplifier subsystem were the major reasons for this choice.

The feedback loop was next closed with an adjustable gain amplifier-modulator. The magnitude of the gain was a critical parameter because too much gain caused oscillation and instability of the whole feedback system. The entire system was connected and tested. It was found that shielding and physical separation of the components was necessary before meaningful measurements could be made and maximum modulation gain could be determined. Coaxial cable and connectors, completely enclosed chassis, and radio frequency filters were employed to substantially reduce radio frequency pick-up. It was then necessary to design and construct a low pass filter to be included in the feedback loop to allow higher amplifier-modulator gain in the 0-500 Hz frequency range of interest without oscillation at higher frequencies.

Overall tests and evaluations of the system's ability to substantially reduce the unwanted amplitude fluctuations of the laser beam were made and found to be very satisfactory.

CHAPTER IV

SYSTEM PERFORMANCE

Measurement Conditions

The conditions under which measurements were taken and data recorded on the complete system will be described below. The laser, all system components, and measuring equipment were run for at least one half hour before taking data. This allowed the equipment and helium-neon gas mixture to reach stable operating temperatures. A decrease in laser light amplitude with increasing temperature and frequency shift of the spectrum analyzer with changing temperature was particularly noticable.

With the radio frequency amplifier's grid bias set at -80 volts and with the amplifier-modulator gain set to zero, the Collins exciter output was adjusted for maximum laser light output as shown by the output voltage of the dc amplifier. The anode voltage of the photomultiplier tube was then adjusted to set the output of the dc amplifier at -0.5 volts dc, which caused the photomultiplier to deliver its maximum current (-10 microamperes) to the dc amplifier. The grid bias was decreased to place the operating point of the system on the linear portion of the dc amplifier output voltage versus the radio frequency amplifier grid bias curve as previously shown in Figures 2, 3, and 4.

To unify data an average dc amplifier output of -4.5 volts was chosen as the operating point. With the amplifier-modulator gain set at zero, there was no feedback and data for the open loop, free running laser was taken. To implement the feedback control system, the gain of the amplifier-modulator was increased to maximum, and if necessary, the grid bias supply adjusted to maintain -4.5 volts at the output of the dc amplifier. Data was also taken in the feedback configuration. All radio frequency filters were tuned to give minimum radio frequency voltage on the oscilloscope screen.

System Tests

Normal Environment Operation

The laser with the complete feedback system as described in Chapter II under normal environmental conditions was tested to determine its ability to substantially reduce unwanted amplitude fluctuations of the envelope of the detected laser beam.

A Tektronix 545B oscilloscope with the 1A1 dual-trace plug-in unit was employed as a means of observing and measuring the envelope waveform of the received laser beam at the output of the dc amplifier. The oscilloscope rise time is given by the manufacturer as 11 nanoseconds and voltage calibration accuracy as 3 per cent. A Singer Metrics Panalyzor Model SB-12b Spectrum Analyzer was used to simultaneously obtain the spectrum of the laser beam envelope at the output of the dc amplifier. Also a Hewlett Packard Model 410B vacuum tube voltmeter was used to monitor the dc level at the output of the dc amplifier.

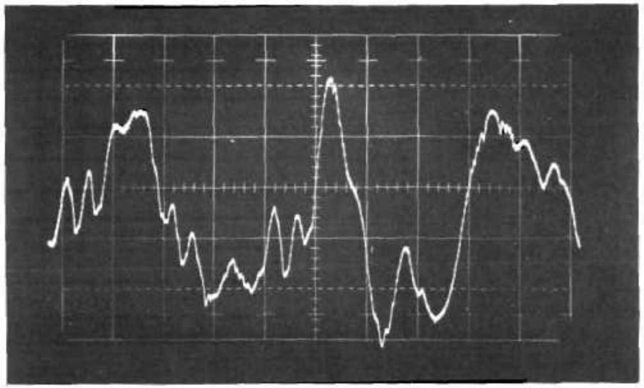
Permanent records of the oscilloscope trace and spectrum analyzer trace were made with a Dumont 302 oscilloscope record camera. Polaroid type 47 film was used with f11 and bulb shutter conditions to obtain single trace photographs.

Three sets of photographs are presented in Figures 14, 15, and 16 for each of the small, medium, and large iris settings, respectively. Photographs (a) and (c) of each figure are the oscilloscope traces and the spectrum analyzer traces are photographs (b) and (d). Sweep rate of the oscilloscope was 10 milliseconds per division and sensitivity of 0.1 volts per division with the dc level at -4.5 volts. The abscissa of the spectrum analyzer trace is frequency scaled 15 Hertz per division for 0-150 Hz, while the ordinate is the relative linear magnitude of the frequency component present in the laser beam envelope. Note, that in all spectrum analyzer traces, the zero frequency or dc amplitude is considerably off scale. This was done to enhance the higher frequency components of the spectrum.

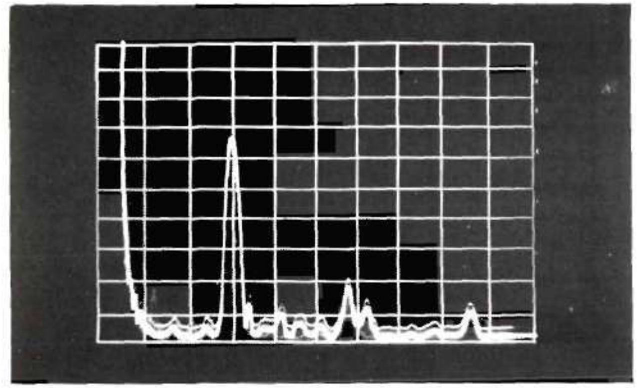
In each of Figures 14, 15, and 16, photographs (a) and (b) are the output of the dc amplifier as a function of time and its frequency spectrum, respectively, with the laser running free without feedback control. Photographs (c) and (d) in the same figures show the output of the dc amplifier with the feedback system operating with maximum feedback control, with no change in either oscilloscope or spectrum analyzer settings. An amplitude fluctuation reduction of 100-500 was measured depending on the size of the iris, with larger reduction for larger iris setting.

Applied Vibration Operation

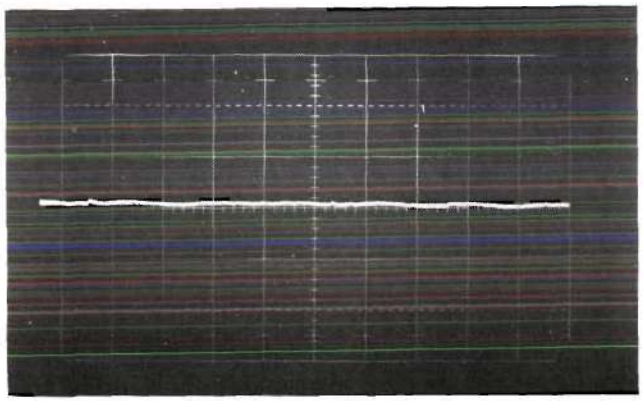
To measure the system's ability to reduce amplitude fluctuations under adverse conditions, external vibration was applied to the laser cavity to increase amplitude fluctuations by a factor of five or more. To duplicate as many as possible of the naturally occurring disturbances



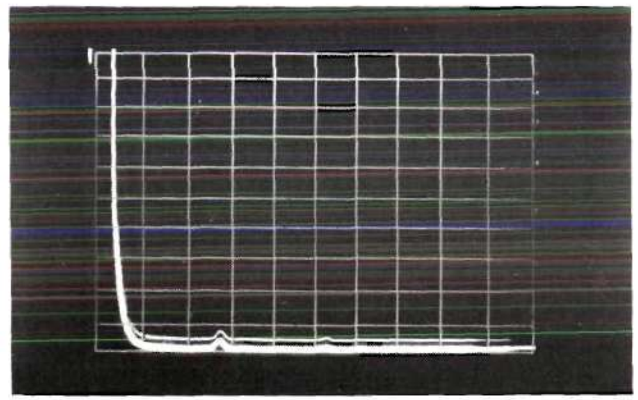
(a) Oscilloscope Trace, Free Running Laser



(b) Spectrum Analyzer Trace, Free Running Laser

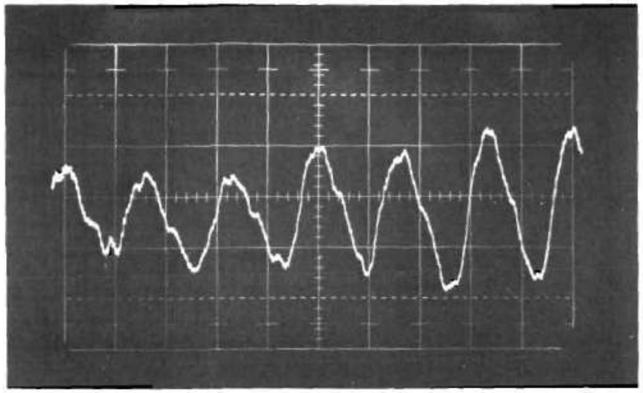


(c) Oscilloscope Trace, With Feedback Control

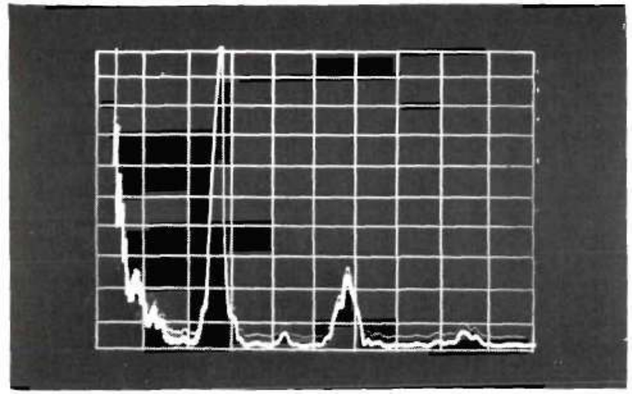


(d) Spectrum Analyzer Trace, With Feedback Control

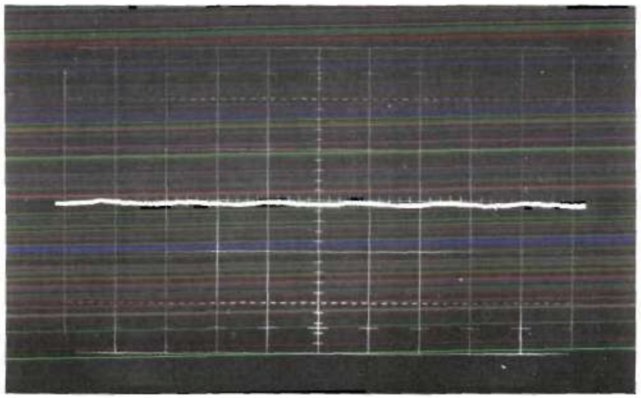
Figure 14. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, with Normal Operation Conditions and Small Iris Setting



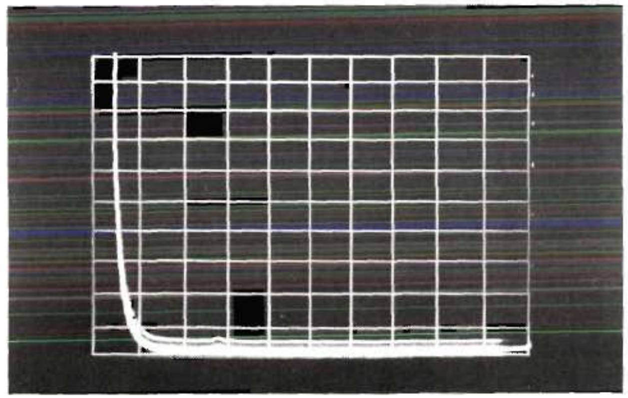
(a) Oscilloscope Trace,
Free Running Laser



(b) Spectrum Analyzer Trace,
Free Running Laser

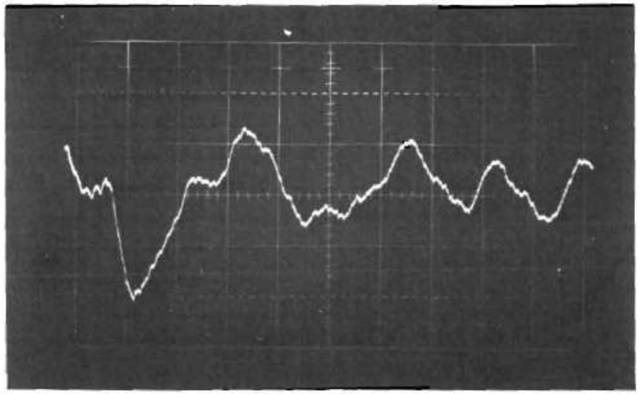


(c) Oscilloscope Trace,
With Feedback Control

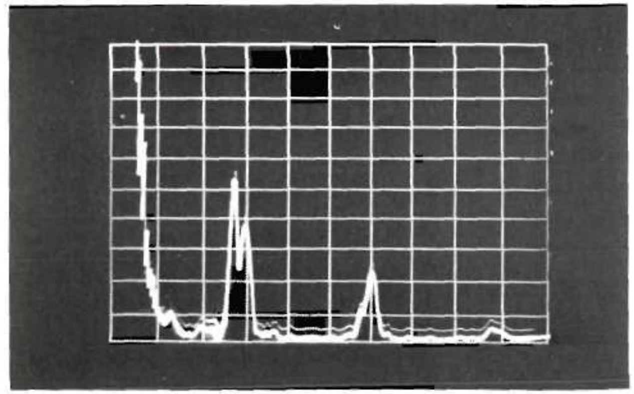


(d) Spectrum Analyzer Trace,
With Feedback Control

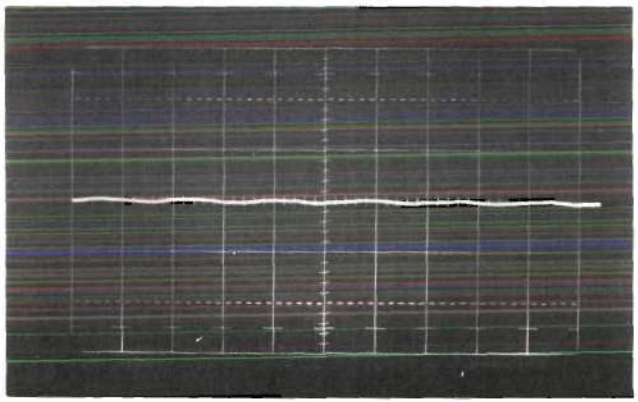
Figure 15. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, with Normal Operating Conditions and Medium Iris Setting



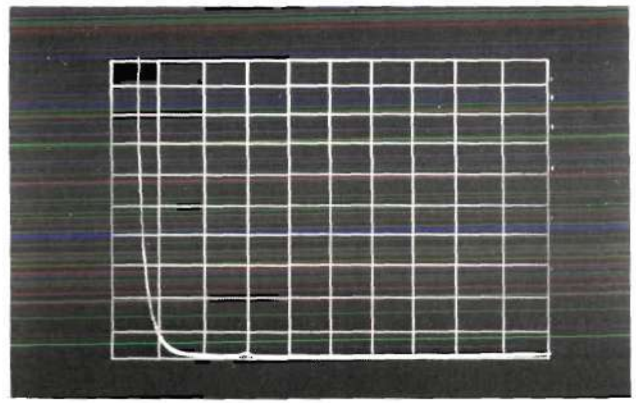
(a) Oscilloscope Trace,
Free Running Laser



(b) Spectrum Analyzer Trace,
Free Running Laser



(c) Oscilloscope Trace,
With Feedback Control



(d) Spectrum Analyzer Trace,
With Feedback Control

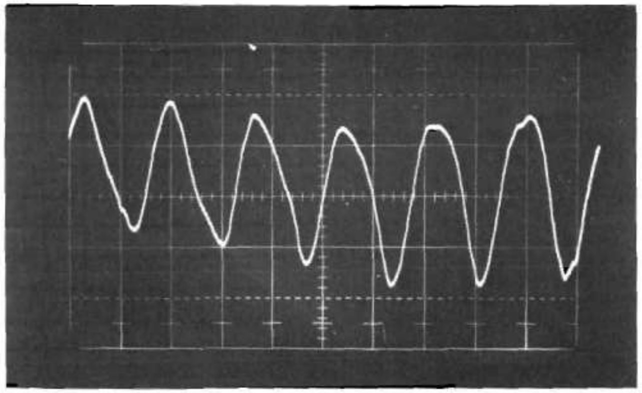
Figure 16. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, with Normal Operating Conditions and Large Iris Setting

in the environment of the laser cavity, an electric fan was set on the wooden table holding the laser and aimed at one of the cavity mirrors, thereby introducing mechanical vibration of the mirror due to direct mechanical vibrations from the fan motor and acoustic and pressure disturbances from the fan blades. Figures 17, 18, and 19 show the results of that test. As explained above in the section on normal operation, photographs (a) and (c) are oscilloscope traces and (b) and (d) are spectrum traces. All scales on the oscilloscope and spectrum analyzer traces are the same as before except the sensitivity of the oscilloscope was decreased to 1.0 volts per division in Figure 18 and 19 for the medium and large iris settings, respectively. As before, photographs (a) and (b) show the fluctuations of the open loop system and photographs (c) and (d) show the fluctuations of the system with maximum feedback control applied. The amplitude of the reduction of the unwanted fluctuations was measured and found to be a factor of 100 to 300, with the larger reduction associated with the larger iris setting. A notable difference occurred in all spectrum traces between the normal and applied vibration operation. In the normal operation, a low frequency peak of amplitude fluctuation occurred from 35-40 Hertz, but in the applied vibration operation this peak of low frequency disturbance shifted to 15-20 Hertz. No explanation for this particular frequency shift of fluctuation is given, but it is noted that the applied vibration had a dominating effect on the spectrum of the envelope of the received laser beam.

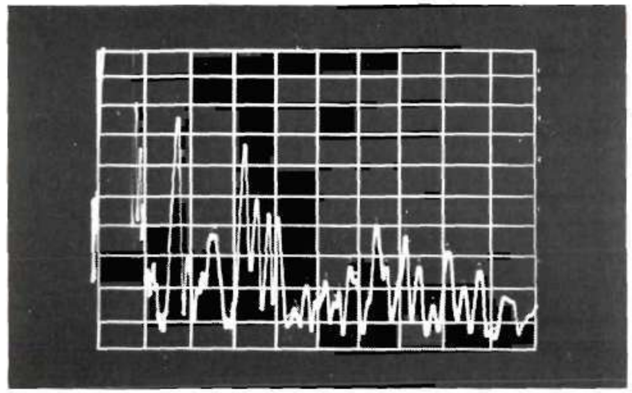
System Limitations

Range of Amplitude

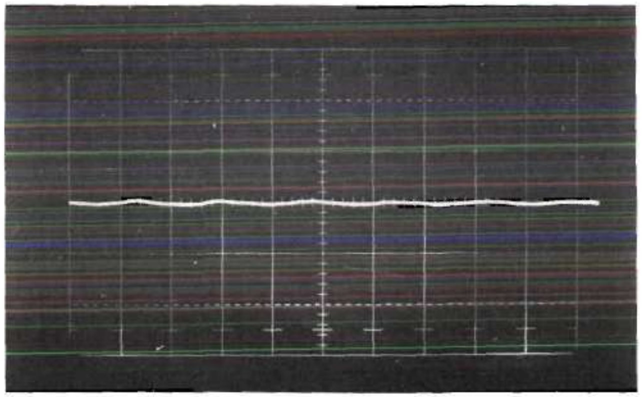
Because the system was designed to operate in the linear portions



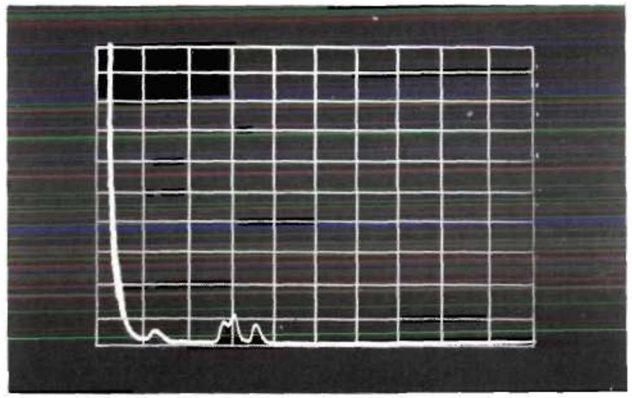
(a) Oscilloscope Trace,
Free Running Laser



(b) Spectrum Analyzer Trace,
Free Running Laser

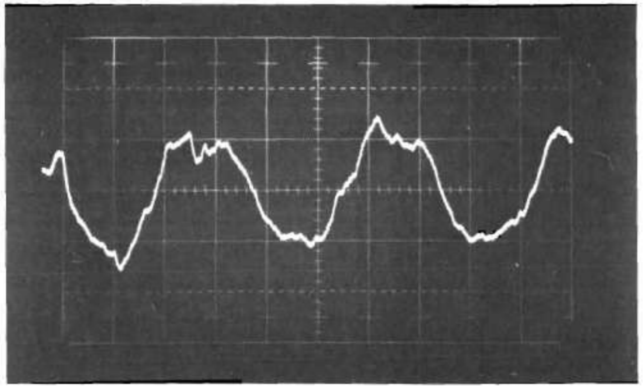


(c) Oscilloscope Trace,
With Feedback Control

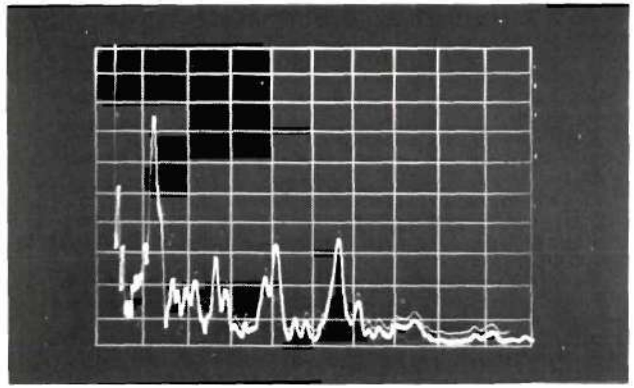


(d) Spectrum Analyzer Trace,
With Feedback Control

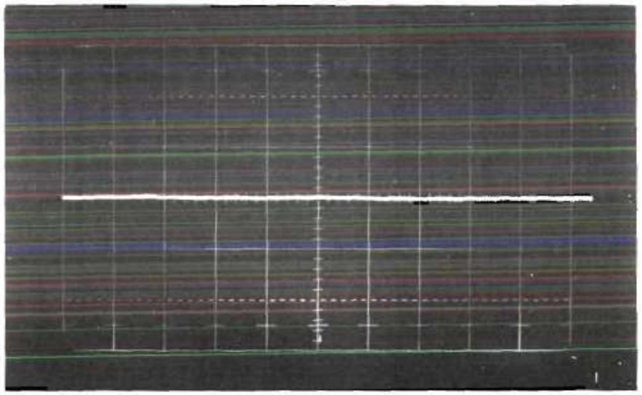
Figure 17. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, With Applied Vibration Conditions and Small Iris Setting



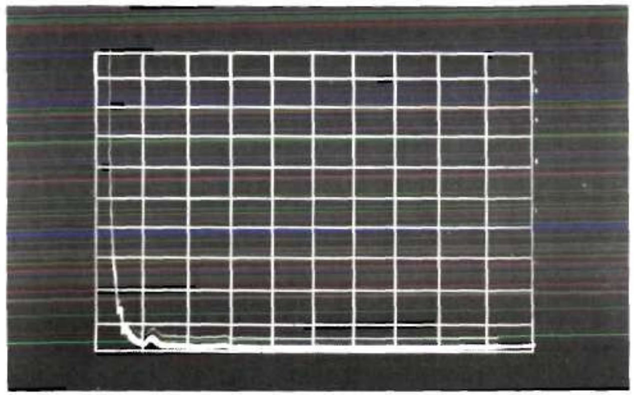
(a) Oscilloscope Trace,
Free Running Laser



(b) Spectrum Analyzer Trace,
Free Running Laser

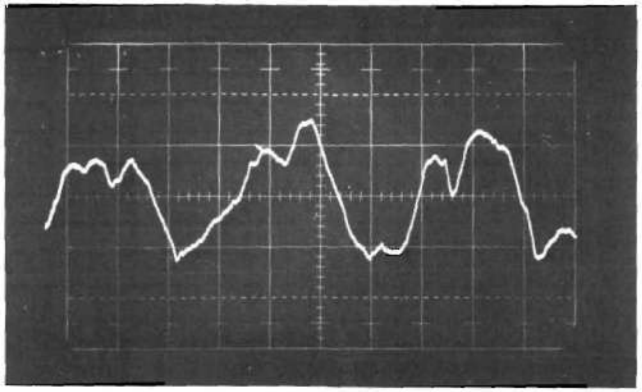


(c) Oscilloscope Trace,
With Feedback Control

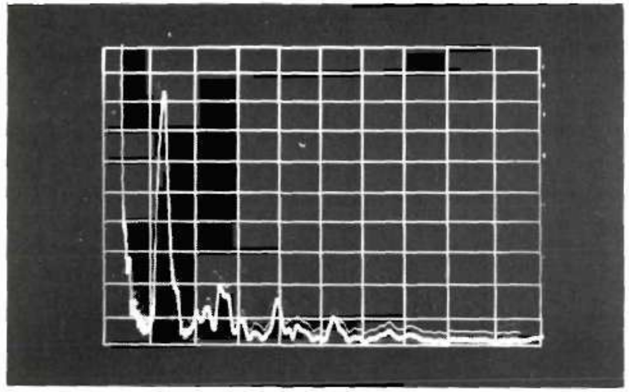


(d) Spectrum Analyzer Trace,
With Feedback Control

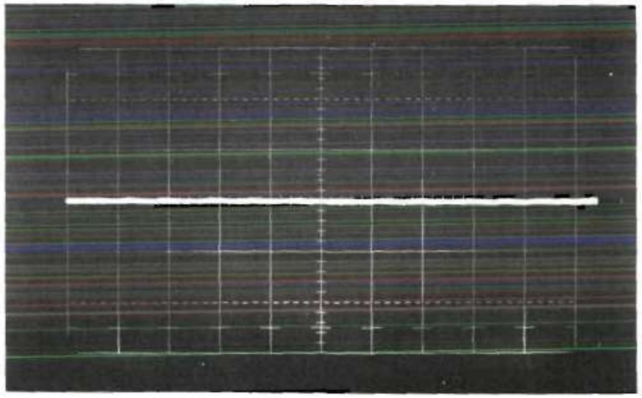
Figure 18. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, with Applied Vibration Conditions and Medium Iris Setting



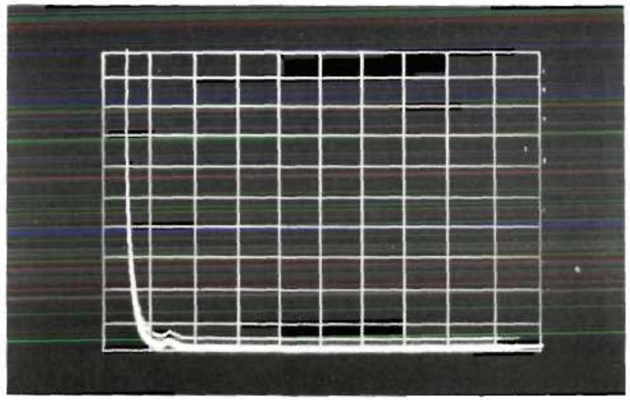
(a) Oscilloscope Trace,
Free Running Laser



(b) Spectrum Analyzer Trace,
Free Running Laser



(c) Oscilloscope Trace,
With Feedback Control



(d) Spectrum Analyzer Trace,
With Feedback Control

Figure 19. Amplitude Fluctuation as a Function of Time and Its Frequency Spectrum, with Applied Vibration Conditions and Large Iris Setting

of the characteristic curves of the various components of the system, the system is limited to these regions. Although over 75 per cent of the range of laser light amplitude output can be controlled with this electronic feedback system, the region of maximum output cannot be amplitude stabilized effectively by this system.

Range of Frequency

The basic feedback equation is:

$$M = \frac{A}{1 + AB}$$

where M is the overall transfer function of the system with feedback, A is the open loop voltage transfer characteristic of the radio frequency amplifier-laser-photomultiplier-dc amplifier, and B is the voltage transfer characteristic of the amplifier-modulator. If the sign of the product AB becomes negative and larger than one, the feedback becomes positive and reinforces rather than cancels the unwanted amplitude fluctuations and unstable oscillations occur. Thus, when the phase of AB is 180° and its magnitude is equal to one, the system is unstable. Due to the nonlinear nature of practically all transfer functions in this amplitude stabilization system, and the mode hopping phenomenon of the laser producing sudden large increases in intensity, it was found necessary to operate the system with a 90° phase margin. A trade-off between higher gain and higher phase margin was made. This trade-off resulted in an upper cutoff frequency of 500 Hz and a modulation gain of 57 as can be seen in Figures 6 and 9, which display the phase characteristics of the closed loop feedback system. In so doing, the useful range of frequency control was bounded by 500 Hertz. Although most fluctuations are due to low, 10 to 150 Hertz, frequency mechanical vibrations, there is also a small amplitude, wide spectrum noise present up to 100 KHz (1) which cannot be reduced by this system.

Drift of DC Level

The lower cutoff frequency of the electronic feedback system was calculated to be less than 0.1 Hertz due to the capacitive coupling between the dc amplifier and the amplifier-modulator. As a result, very slow, long-term drifting of the operating point occurs. As an example, the dc level of the output of the dc amplifier may change one-half of a volt in thirty minutes. Because the system is not exactly linear, straight dc coupling does not improve this situation. An integrator type error detector, comparing the received signal to a fixed reference voltage over a finite time interval would be a possible solution to the drift problem.

CHAPTER V

RESULTS

An helium-neon laser can be amplitude stabilized with the electronic feedback system described in this thesis. The amplitude fluctuation of an helium-neon laser mounted, as is normal, on an optical bench which is shock mounted to a solid foundation can be reduced by a factor of one hundred or more. Higher amplitude fluctuation reductions can be obtained if the helium-neon laser is operated at near maximum output power. In this mode of operation, amplitude fluctuations can be reduced by a factor of three hundred or more.

The applied vibration test demonstrated that the electronic feedback system described herein can reduce by the same factors the unwanted amplitude fluctuation even under non ideal mounting and environmental conditions.

CHAPTER VI

CONCLUSIONS

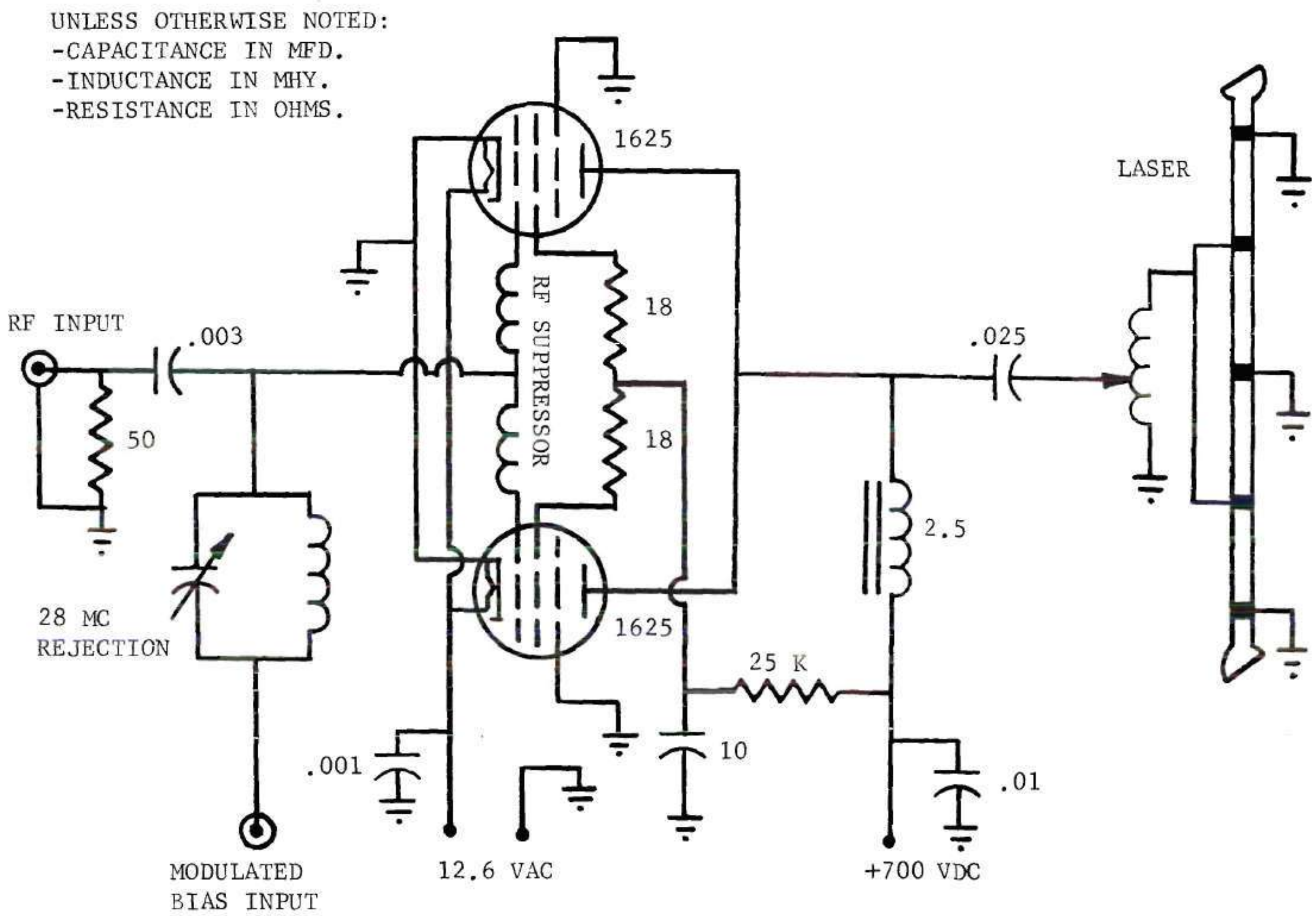
An helium-neon gas laser beam is found to fluctuate in amplitude as a result of mechanical vibration of its cavity components induced by mechanical, acoustical, temperature, and pressure disturbances inherent in its environment. Even when great care is taken to overcome environmental disturbances, amplitude fluctuations persist to some degree. Mirror movement as small as 10^{-4} centimeters cause measurable amplitude fluctuations. The electronic feedback system described in this thesis can compensate for these mirror movements and produce an amplitude stable output laser beam.

For many communication and measurement applications of the helium-neon gas laser beam, strict amplitude control is necessary while strict frequency control is not. Base-band time division-multiplexing (8) and amplitude modulation laser communication schemes require only a constant amplitude laser beam which is modulated or multiplexed and then received on a wide band light amplitude detector, and thus, no concern for frequency stability is required. Interferometer length measurements in which distance can be measured to within a wavelength of laser light, again, only require a fixed amplitude laser beam. As the electronic amplitude stabilization feedback system described in this thesis can compensate for non ideal mounting of the laser cavity and non ideal environmental conditions, this system can be employed in communications and measurement systems which may have severe environmental conditions for an helium-neon gas laser.

The amplitude stabilization feedback system required only conventional amplitude modulation of the laser exciting radio frequency discharge, a light detector, and a low frequency amplifier. The cost and ease of implementation are small compared to complete mechanical, acoustical, thermal and pressure isolation of the helium-neon laser cavity.

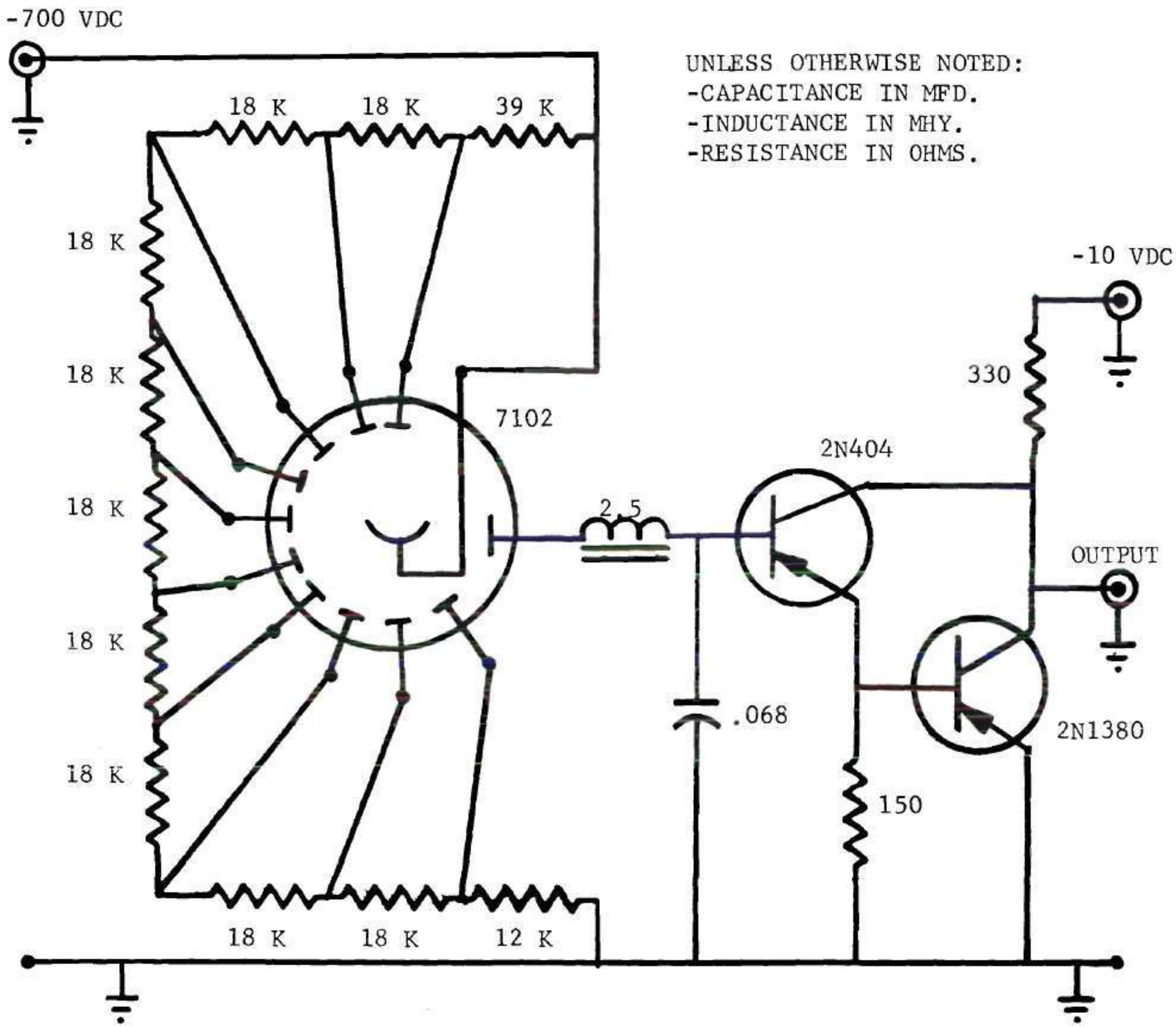
APPENDIX A

RADIO FREQUENCY AMPLIFIER SCHEMATIC DIAGRAM



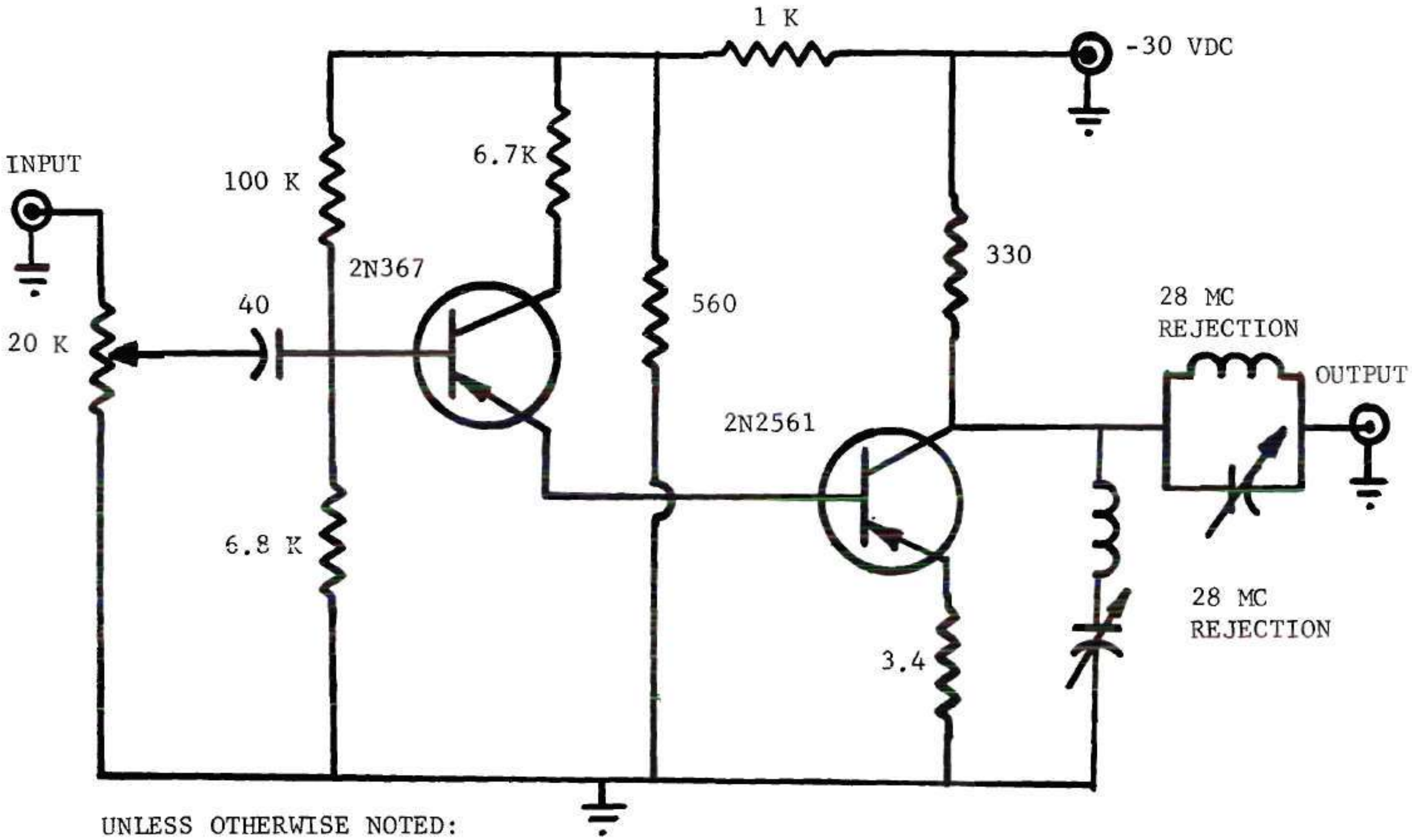
APPENDIX B

PHOTOMULTIPLIER AND DC AMPLIFIER SCHEMATIC DIAGRAM



APPENDIX C

MODULATOR-AMPLIFIER SCHEMATIC DIAGRAM



UNLESS OTHERWISE NOTED:
-CAPACITANCE IN MFD.
-INDUCTANCE IN MHY.
-RESISTANCE IN OHMS.

APPENDIX D

OPERATING INSTRUCTIONS

To Turn on Laser:

1. Connect all equipment as shown in the block diagram and schematic diagrams.
2. Apply -80 volts dc to the radio frequency amplifier control grids.
3. Apply 12.6 volts ac to the radio frequency amplifier filaments.
4. Apply 700 volts dc to the radio frequency amplifier plates after one minute's warm-up time of the two Lambda power supplies.
5. Apply 10 watts of 28 MHz power from the Collins transmitter to the control grids of the radio frequency amplifier using a standing wave meter between the radio frequency amplifier and the Collins transmitter to insure that no power is reflected back to the Collins transmitter.
6. Adjust the output of the Collins transmitter to obtain desired laser output power.

To Receive Laser Beam:

1. Apply -10 volts dc to the collectors of the dc amplifier located in the photomultiplier tube housing chassis.
2. Apply 700 volts dc from the Kepco power supply to the anode of the photomultiplier tube.

3. Measure dc amplifier output voltage and adjust the Kepco power supply voltage to give dc amplifier output voltage of -4.5 volts dc.

To Amplitude Stabilize Laser Beam:

1. Set gain of modulator to zero.
2. Apply -30 volts dc to modulator collectors.
3. Adjust -80 volt dc bias supply to place operation of the laser on the linear region of the exciter-laser-detector transfer characteristics.
4. Adjust Kepco power supply voltage to give dc amplifier output voltage of -4.5 volts dc.
5. Monitor the input and output voltages of the modulator on a dual trace oscilloscope.
6. Increase gain of the modulator slowly until desired level of control is obtained. Excess gain will cause oscillation of the control system.

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